A Preliminary Study of

MARS ROVER/SAMPLE RETURN MISSIONS

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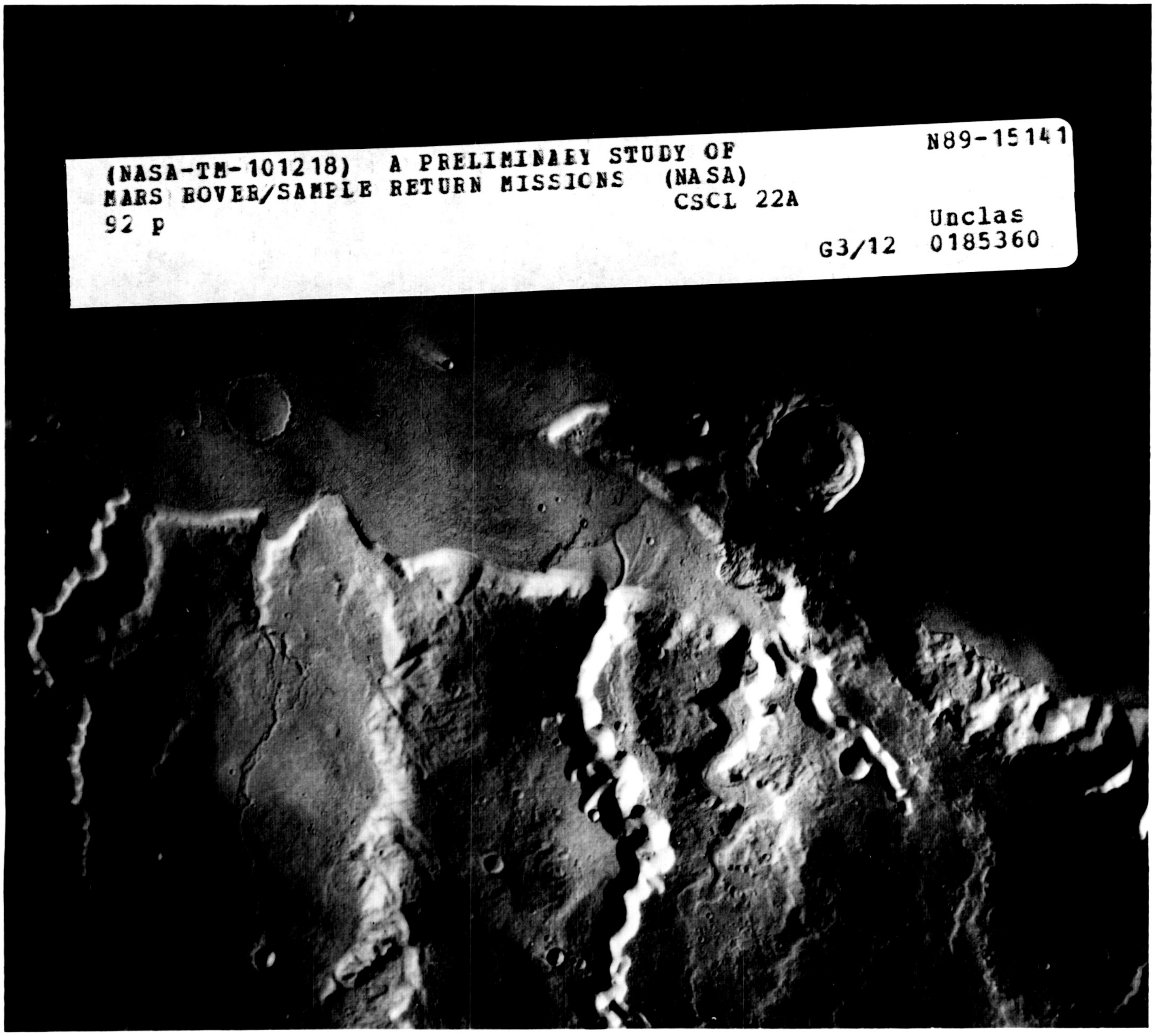

conducted by

The Mars Study Team
Solar System Exploration Division
NASA Headquarters

January 1987

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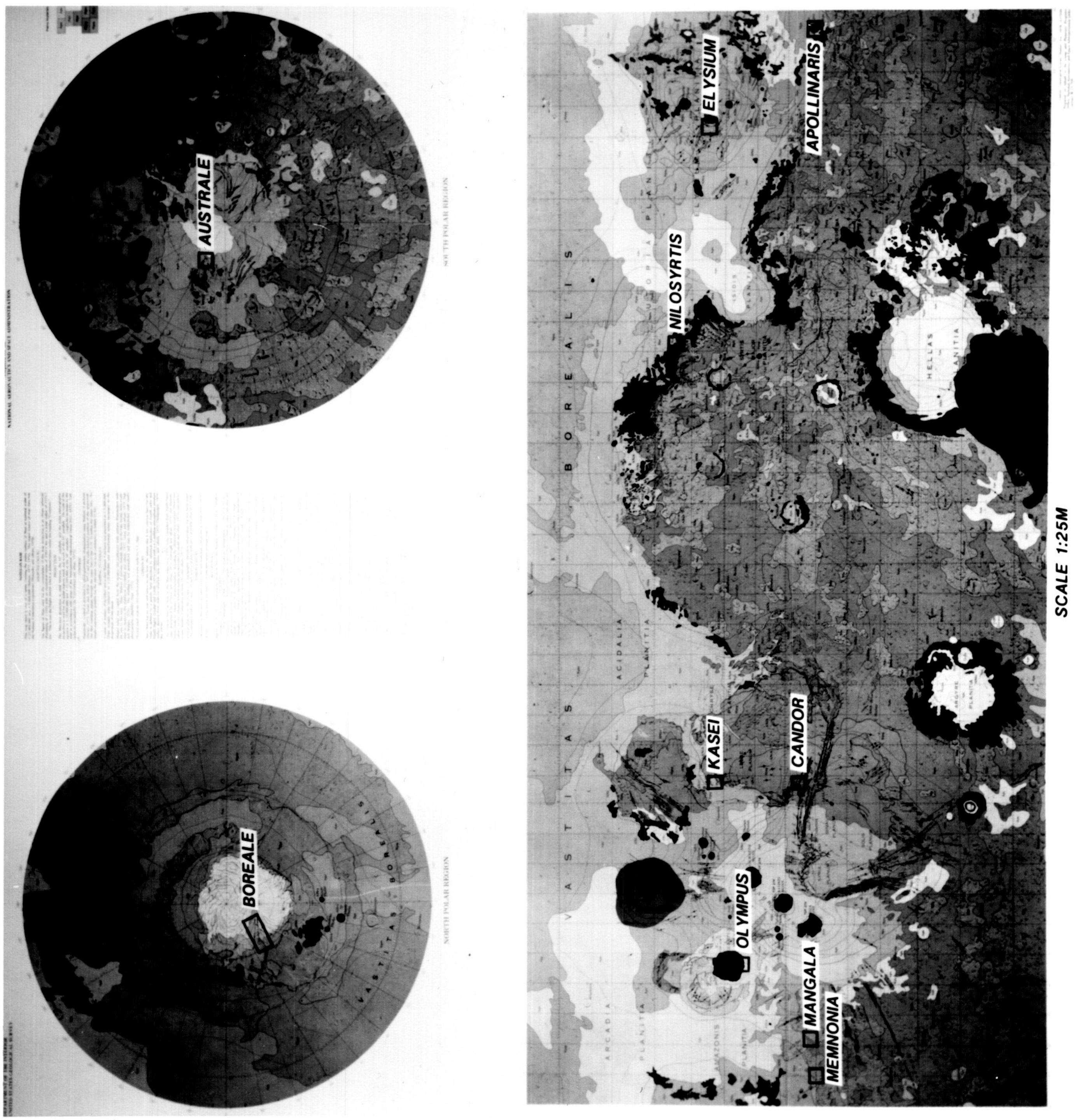
Cover *The East Mangala region of Mars is a candidate landing site for a Mars Rover/Sample Return mission.*



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FOREWORD

In the summer of 1976 two magnificently instrumented robot spacecraft settled softly on the surface of our sister planet Mars, bringing home for all mankind an image of another world on the scale of our own backyard. The twin Viking landers and their orbiter partners were fabulously successful. They lasted for years as interplanetary investigators, mapping the planet to create stunning images and characterizing the surface at two distinct places.

Viking was the culmination of almost two decades of engineering and scientific work to learn about our red neighbor. Mars had been investigated first in the early 60s by Mariner flybys. Some years later, in 1971, a Mariner orbiter greatly increased our understanding of Mars by showing us great volcanoes and canyons whose scales were unknown on the planet Earth. The Mariner orbiter paved the way for the morning of July 20, 1976, when, after weeks of intense site selection and certification activity, Viking 1 landed safely at Chryse Planitia, "The Plains of Gold," on Mars.

Ten years have passed since the Viking landings and no new probes from the planet Earth have been launched to Mars. To those who dedicated years of their lives to the success of Viking, it would have been heresy to suggest that Viking was the end of an era. But it was. Now, after a significant hiatus, Mars once again looms as a major target for exploration that will finally build upon the legacy of the Mariners and Vikings. The Soviet Union has defined a series of projects, beginning with the ambitious Phobos mission to be launched in 1988, that will unveil more of the scientific secrets of Mars. And an American spacecraft, Mars Observer, will return to Mars in the early 1990s to obtain global scientific data.

For years, scientists throughout the world have insisted that the next really important scientific step forward in our understanding of Mars will come when we return a sample of the surface home for analysis in Earth laboratories. That mission, although complex and expensive, is now within the technological capability of at least two space powers on Earth. The project could be done by either of them alone or by the two of them together as an example of international cooperation.

So the time seems to have come again for Mars. It appears indeed likely that a sample return mission to the Red Planet will be launched within the next 15 years. This report presents the results of a preliminary study that was directed primarily at one design issue: Does there exist a reasonable technical plan in which two roughly equal partners participate in a conjoint mission to return a scientifically interesting sample from Mars and do NOT engage in significant technology transfer?

A separately launched mission involving a martian rover and a sample return vehicle might be such a project. The rover would roam across varied terrain, taking and marking and storing samples, before bringing its cache of scientific jewels to an ascent vehicle that landed separately on the surface of Mars. The two missions would be essentially disjoint, except for the handshake exchange of about five kilograms of martian surface material and the sharing of this same material after the arduous trip back to Earth. It is this separate mission (emphasizing the rover portion because of the recent documented studies on sample return missions) that is studied in this report.

There are three possible scenarios for American involvement in a Mars Sample Return mission and it is NASA's intent to be prepared for any of them. During 1987 and 1988 studies will be conducted of technological issues associated with our doing EITHER HALF of the mission suggested in this report, as well as a full-up, unilateral sample return mission. The goal of the coming studies, which are natural follow-ons to the effort documented in this report and in the previous studies of sample returns, is to define the technological data base from which we may proceed into more detailed spacecraft, mission design, and technology studies.

Finally, after a decade, momentum is building for a return to Mars. There is an almost palpable excitement now in the discussions of future Mars missions. There is also an understanding that we, as a species, seem finally to be ready to expand upon the outstanding achievements of all those scientific pioneers who began the exploration of the planets.

Gentry Lee

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EXECUTIVE SUMMARY

The Solar System Exploration Committee (SSEC) of the NASA Advisory Council has strongly recommended that a Mars Sample Return mission be undertaken before the year 2000. This mission, which includes a surface rover, will provide a wealth of scientific information about Mars and will increase our understanding of the origin and evolution of all terrestrial planets, including Earth. It will also present major technological challenges and stimulate advances in many critical areas of spacecraft design and operation.

Comprehensive studies of a Mars Sample Return mission have been ongoing since 1984. The initial focus of these studies was an integrated mission concept with the surface rover and sample return vehicle elements delivered to Mars on a single launch and landed together. This approach, to be carried out as a unilateral U.S. leadership initiative, is still a high priority goal in an Augmented Program of exploration, as the SSEC recommendation clearly states.

With this background of a well-understood mission concept, NASA decided to focus its 1986 study effort on a potential opportunity not previously examined; namely, a Mars Rover/Sample Return (MRSR) mission which would involve a significant aspect of international cooperation. As envisioned, responsibility for the various mission operations and hardware elements would be divided in a logical manner with clearly defined and acceptable interfaces. The U.S. and its international partner would carry out separately launched but coordinated missions with the overall goal of accomplishing *in situ* science and returning several kilograms of surface samples from Mars. Important considerations for any proposed implementation of such a plan are minimum technology transfer, maximum sharing of scientific results, and independent credibility of each mission role.

Under the guidance and oversight of a Mars Exploration Strategy Advisory Group organized by NASA, a study team was formed in the fall of 1986 to develop a preliminary definition of a flight-separable, cooperative mission. The study objective was to examine at least one plausible mission concept in sufficient depth to identify and assess key technical issues and determine performance feasibility. The selected concept assumed that the U.S. would undertake the rover mission with its sample collection operations and our international partner would return the samples to Earth. Although the inverse of these roles is also possible, this study report focuses on the rover functions of MRSR because rover operations have not been studied in as much detail as the sample return functions of the mission.

MISSION DEFINITION

The overall mission scenario is illustrated in Figure A. Both the rover and sample return lander systems are launched during the same opportunity window to arrive at Mars within a month of each other. Optimistically, this first launch sequence could occur as early as 1996, with a second launch in 1998, to complete a two-site sample return objective. A Shuttle/IUS vehicle is capable of launching the rover mission, which has an injected mass requirement of about 3,000 kilograms, if aerocapture is used for Mars orbit insertion; a more capable launcher like the Titan IV/Centaur would be needed if all-propulsive capture into Mars orbit is used. Total injected payload for the sample return mission is about three times more massive than the rover mission payload since this launch provides both the Mars ascent vehicle and the Earth return vehicle. This requirement may exceed the near-term, single launch capability of any international partner; Figure A depicts a dual launch scenario, with assembly of payload elements in low-Earth orbit followed by a single transfer to Mars.

Upon arrival at Mars, each of the separate vehicle systems is inserted into Mars orbit; aerocapture is the preferred design option because its mass requirements are lower than all-propulsive capture. The nominal orbit for rover mission deployment is elliptical with low-altitude periapsis and orbit period equal to one Mars day; the spacecraft left in orbit provides surface imaging and relay telecommunications support to the rover mission. The sample return system may initially be placed into a similar orbit or, possibly, directly into a near-circular orbit for later rendezvous. After a period of

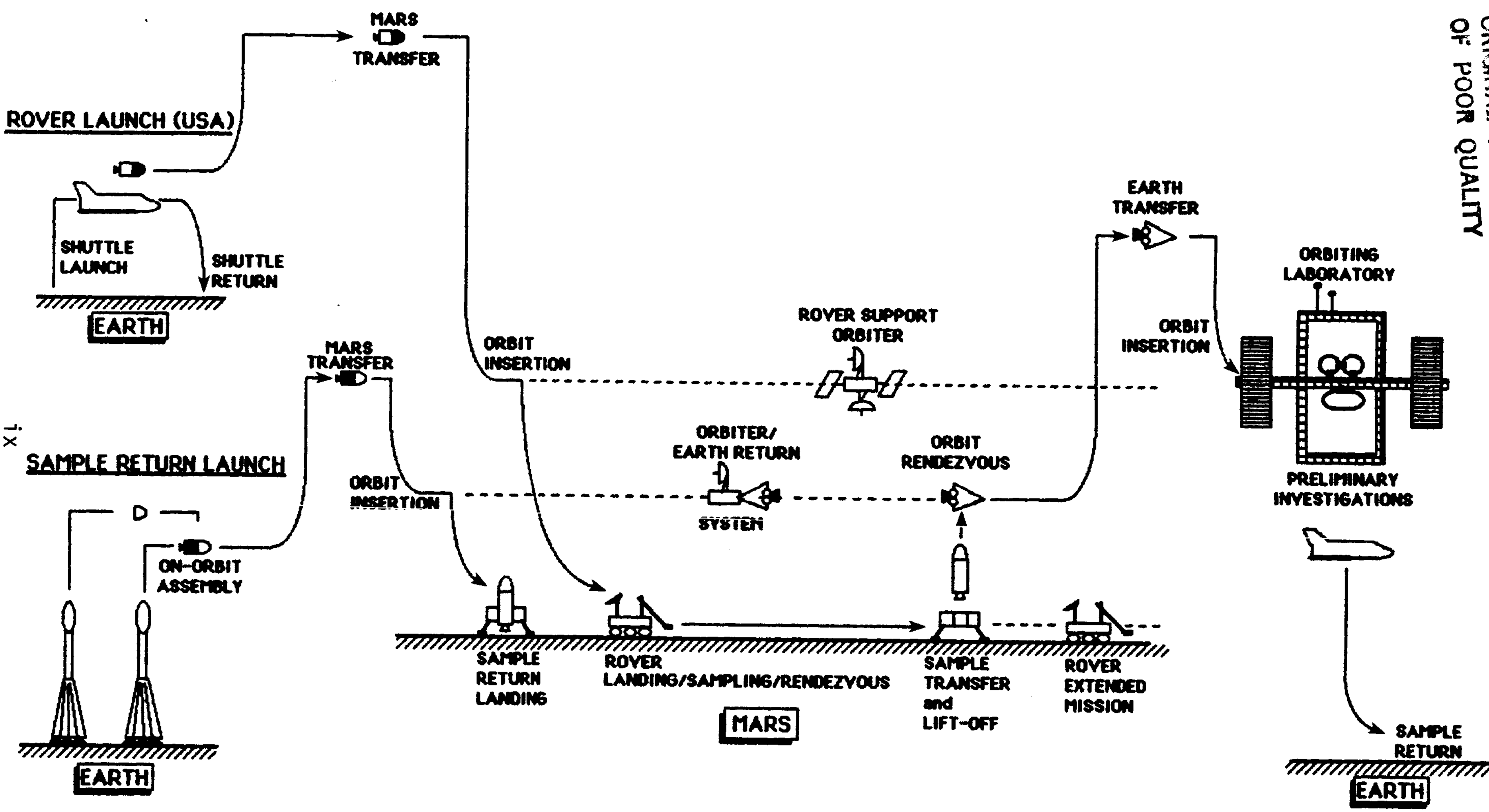

Figure A. Mars Rover/Sample Return Mission Scenario coordinated orbital reconnaissance to certify the safety of the preselected landing site, the two landers are deorbited to land fairly close to each other to enhance later surface rendezvous/sample transfer operations. Nominally, the sample return system lands first to provide a deterministic reference point for targeting the rover lander. Sample transfer may be performed in several sorties, depending on both the landers' separation distance and the location of desired sampling sites. It is expected that the sample return lander will have the independent capability of acquiring samples at its landing site and surrounding area.

The typical stay time at Mars for low-energy round trips of about 2.8 years is between 11 and 18 months, depending on the launch year. Much of this time would be available for rover science/sampling operations prior to liftoff of the ascent vehicle. Although the remainder of the sample return mission in this scenario is not primarily the responsibility of the U.S., certain assumptions could be made. For example, it is assumed that Mars orbit rendezvous would be used as part of the return process. Another expectation is that the samples would be returned to an Earth orbiting laboratory for preliminary investigations, including quarantine protocol testing. Although undoubtedly of great concern, the specific procedures for sample recovery and control were not addressed in this study. Nonetheless, such procedures would certainly be the focus of future international discussions and agreements.

SCIENCE OBJECTIVES

The MRSR mission must be scientifically successful both as a sample return mission and as a surface science mission. Intensive study of Mars will determine: (1) the chemical, mineralogical, and petrological character of a range of returned samples; (2) the nature and chronology of the martian surface-forming processes; and (3) the distribution, abundances, sinks, and sources of volatiles, including the investigation of both past and present biological potential. A variety of carefully selected and documented samples will be obtained, and proper precautions must be taken to preserve the chemical and physical integrity of the samples during the collection process and the return trip to Earth. The suite of samples will be obtained from in-place rocks, pebbles, surface and subsurface soils, ices and volatiles, and the atmosphere. Typical sampling tools include a coring drill, chipper, rake, scoop, molecular sieve, and dust collector, many under the control of a robotic rover arm. In support of the sampling operations and as important experiments for *in situ* science, the rover's science payload will include instruments of the following generic types: imager, elemental analyzer, water analyzer, atmospheric and evolved gas analyzer, and mineral characterizer.

LANDING SITES

Site selection is driven by science objectives, landing accessibility, and safety. Terrain studies of candidate landing sites are being conducted to evaluate the geology and trafficability of each site. There is general agreement that the mission should sample a variety of terrains and materials. An optimum site would have geologic units of widely diverse ages and chemical compositions; these units should be close enough to be reached by a roving vehicle with moderate mobility capability (no more than 100 kilometers). More than ten candidate sites have been identified and characterized based on high-resolution Viking photographs and the derived geologic maps of these areas. Most of these sites lie within 25 degrees latitude of the Mars equator; rover traverses have been generated for Candor Chasma and Mangala Valles; the latter has more varied and seemingly smoother terrain. There is also considerable interest in sampling the ice and layered deposits of the north and south polar regions. Polar sites are not as easily accessible from elliptical orbits as near-equatorial sites, but they do appear to be the smoothest areas on the planet.

CONCEPT ISSUES

A number of key technical issues emerged during the course of this study. A preliminary understanding of these issues is important to their eventual resolution, which may have a significant impact on the performance achievement, development cost, and technical risk of the overall mission concept.

Site Safety Certification. Choosing a safe landing site within an interesting scientific area requires sufficient information about the site to establish the guidance and configuration design of the landing system. Certification implies the existence of safe touchdown locations that can be identified and reached by a lander capable of hazard avoidance and/or hazard tolerance. Four different landing design options that depend on various levels of information about surface characteristics were defined. The first option relies totally on prior information obtained from high-resolution orbiter images (e.g., Mars Observer and follow-on precursor missions) and radar data; this option requires the most structurally robust landing system design. The second option applies onboard lander instrumentation to identify hazards during the terminal landing phase and uses propulsive maneuvering to avoid the most dangerous obstacles; the benefit in this case is a smaller-scale lander. Option 3 introduces new data taken by a high-resolution imager on the MRSR orbiter, thus providing a map of the landing area stored in the lander memory for image correlation processing and hazard avoidance maneuvering; the lander scale is further reduced. The fourth option adds terrain correlation techniques during the entry phase and results in the most sophisticated computational design, i.e., the ultimate trade-off favoring electronics over structural robustness.

Orbiter Support Role. Several ways in which the orbiter may assume functions to support the surface operations and minimize the rover's complexity and design risk were studied. Imaging in support of the landing site survey and safety certification has already been mentioned. Orbiter imaging would also benefit long-range traverse planning, allowing a much higher average daily speed for the rover operating in a semiautonomous mode. The third functional role of an orbiter is to serve as a telecommunications relay link between the rover and Earth. This relay, complementing a direct rover-Earth link, greatly extends the rover's operational duty cycle over each martian day for near-equatorial landing sites, and virtually enables successful communications for polar sites. It also serves as a backup to the direct Earth link.

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Landing Strategy. Surface rendezvous is a unique requirement for this mission concept involving separately landed rover and sample return vehicles. Lander guidance accuracy was assessed for different entry configurations. Aeromaneuvering with a vehicle with a moderate-to-high lift-to-drag ratio is very desirable because it offers the smallest landing errors that can be practically achieved (less than 10 kilometers). Analysis of landing sequence options argues for a strategy in which the sample return vehicle is landed first, particularly if its guidance accuracy is not as good as that of the rover lander. This report presents quantitative data on the maximum values of lander separation and rover traverse distances resulting from different targeting strategies and guidance accuracy capabilities.

Rover Mobility. This study focused attention only on local controlled mobility, which is characterized by land-roving vehicles (either wheeled, tracked, or legged) that have relatively precise control over their position and sampling ability. Typical mobility requirements include traversing one kilometer per day, surmounting obstacles of 1.5 meter scale, and climbing grades of up to 35 percent on loose sand. Legged locomotion offers better grade-climbing ability than either wheeled or tracked vehicle types, but may be less reliable because of the greater complexity of its mechanisms and computational requirements. A preliminary design was developed for a three-cab, six-wheeled rover weighing about 600 kilograms (including a 90 kilogram science payload) with a power budget of 240 watts. This analysis helped underscore a very important design issue; namely, that packaging volume constraints imposed by the entry aeroshell, as well as the launch vehicle payload envelope, act to limit the rover size and, therefore, the scale of surface obstacles that can be traversed.

Sample Thermal Control. The primary curatorial concerns regard the retention of information associated with the volatiles, and the subtle information associated with low-temperature transformations within the samples of rocks, soils, and ices. A clear preference is for acquiring the samples without thermal contamination and then preserving the samples in a cold condition

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(less than 240 K) when stored on the rover and in the return spacecraft. The largest thermal threat identified is the heating of the return capsule as it orbits Earth awaiting recovery. The preliminary conclusion of the studies to date is that the martian samples can be returned to Earth in a cold state with proper thermal control methods which do not require excessive mass or power.

MISSION FEASIBILITY ASSESSMENT

Based on the analysis of the key technical issues and preliminary design concepts, it is concluded that a flight-separable MRSR mission conducted in a cooperative international mode as defined here would be technically feasible. Aside from programmatic or political issues which were not treated here, it appears that the necessary technology to accomplish a U.S. rover mission is either at hand or will be available in the near term, and that the first mission could be launched as early as 1996 or 1998. Table A presents a mass summary for a plausible reference design and indicates that our current launch capability (i.e., Shuttle/IUS or the anticipated Titan IV/Centaur) is sufficient to perform the rover mission with adequate margin. Initial cost estimates indicate a significant savings for the rover-only mission compared to a full-up, unilateral Mars sample return.

The mission concept suggested in this study, as well as the results obtained, should be considered preliminary. All technical issues need to be addressed again in greater depth, as they will be in the studies planned to be conducted in 1987-88 by several NASA centers and aerospace industry contractors. NASA intends to be prepared for any opportunity that may arise regarding Mars sample return. This means that all possible scenarios for U.S. involvement must be reexamined. Basically, three such scenarios exist: either half of the split rover/sample return mission as a cooperative endeavor, or the complete mission as a unilateral initiative. The follow-on studies will examine each of these cases in order to expand the technological data base which, in turn, will enable an informed decision on the most logical approach to follow.

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Table A

MARS ROVER MISSION MASS SUMMARY FOR A PLAUSIBLE REFERENCE DESIGN

	Total Mass in Kilograms			
	Mars Aerocapture[1]		Propulsive Capture[1]	
Rover [2]	607		607	
Lander Module	336	(82)*	336	(82)
Parachute Systems	87		87	
Aeromaneuvering System	469	(106)	469	(106)
Aerocapture Shell	208		---	
Orbiter [3]	894	(289)	1,939	(1,185)
Bioshield	29		29	
LV Adapter	79		104	
Injected Mass	2,709	(477)	3,571	(1,373)
Shuttle/IUS(II) Margin ...... 1996 Launch	740		680	(w/Injection Module)

* Propellant mass in ( )

(1) 500 km x 1 sol orbit

(2) with 90 kg science payload

(3) with 61 kg science payload

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TABLES

FIGURES

FIGURES (concluded)

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1. INTRODUCTION

NASA's guiding strategy for planetary exploration is based on a balanced process of simultaneously investigating the various types of bodies in the solar system: the inner planets, outer planets, and small bodies. Nevertheless, at certain times in this process there exists the unique opportunity for intensive study of a particular body following its scientific reconnaissance and exploration phases. Mars is such a body. The Solar System Exploration Committee (SSEC) of the NASA Advisory Council has strongly recommended that a Mars Sample Return mission be undertaken before the year 2000 (Ref. 1). This mission, which includes a surface rover, will provide a wealth of scientific information about Mars and will increase our understanding of the origin and evolution of all terrestrial planets, including Earth. It will also present major technological challenges and stimulate advances in many critical areas of spacecraft design and operation.

The scientific rationale and objectives for comprehensive in situ exploration of the martian surface, and sample return in particular, have been well established by several committees of the Space Science Board and a number of Mars Science Working Groups. Most recently, the SSEC reconfirmed this basic science strategy, stating in part: "... the return of unsterilized martian samples to Earth is the best and only way to make certain kinds of critical measurements that will determine: (a) the geologic history of martian rock units; (b) the evolution of the martian crust and mantle; (c) the interactions between the martian atmosphere and surface materials; (d) the presence of contemporary or fossil life." The SSEC further stated that a scientifically justifiable Mars Sample Return mission must provide a variety of rationally chosen and documented samples from carefully selected areas, must incorporate significant surface mobility in obtaining adequate samples, and must take proper precautions for preserving the chemical and physical condition of the samples during the collection process and the return trip to Earth.

The most recent comprehensive study of a Mars Sample Return mission was carried out in 1984 by personnel from the Jet Propulsion Laboratory (JPL), NASA/Johnson Space Center (JSC), and Science Applications International

Corporation (SAIC). That study (Ref. 2) focused on an integrated mission concept wherein the surface rover and sample return vehicle elements were delivered to Mars on a single launch and landed together. Design characteristics and technology requirements were investigated for a number of alternative mission options. With this background of a well-understood sample return concept, NASA decided to focus its 1986 study effort on a potential opportunity not previously examined; namely, a Mars Rover/Sample Return mission which would involve a significant aspect of international cooperation. As envisioned, the U.S. would assume a major but not unilateral role in such an implementation mode, which would involve several separate launches of the rover and sample return mission elements with landings at two selected sites on Mars.

The objective of this study is to develop a preliminary definition of a cooperative initiative for a flight-separable Mars Rover/Sample Return (MRSR) mission, and to identify the key technical issues which will form the basis for subsequent focused analyses by NASA and aerospace contractor teams. Toward this purpose, in the fall of 1986 a preliminary study team consisting of members from JPL, JSC, SAIC, the NASA/Ames Research Center (ARC), and the U.S. Geological Survey (USGS) was formed. A Mars Exploration Strategy Advisory Group (MESAG) was organized by NASA to provide oversight support and guidance. Explicit guidelines for this effort were:

1. The MRSR initiative will consist of two separate, coordinated missions of like importance; specifically, a Mars Rover and a Mars Sample Return.

2. One mission will be performed by the U.S. and one by an international partner, with each participant assuming the role that it perceives itself to be most capable of performing.

3. Roles should be defined such that technology transfer is minimized and the sharing of results is maximized.

4. Each mission role should be independently credible in the event that the cooperative effort is abandoned or that the other mission fails.

Guidelines of an implicit nature were that the study should focus on technical rather than programmatic or political issues, that the mission launch should be considered in a time frame as early as 1996 or 1998, and that the near-term U.S. launch capability should be restricted to either the Shuttle/IUS or the Titan IV/Centaur vehicles.

The Mars Sample Return mission based on a single flight system approach remains the top U.S. priority for an Augmented Program mission initiative as clearly stated by SSEC recommendation. Nevertheless, a different view was required in this study in order to properly address the potential opportunity for accomplishing the mission objectives in a cooperative international mode. One directive for the study was to develop a set of plausible options and to analyze these options at a level of detail sufficient to determine the most sensible approach. The preliminary study team began its activities by applying the guidelines stated in the introductory remarks to the question: How should the mission operations and hardware elements be divided; i.e., who does what, and when?

Early attention focused almost exclusively on a U.S. rover mission design role in a joint MRSR mission concept. The rationale for this choice includes the following considerations: (1) given the recent Mars sample return studies, a rover mission is presently the less well understood of the two role options; (2) our projected near-term launch vehicle capability cannot capture a Mars sample return mission with a single launch, but would very likely be capable of carrying an orbiter and rover lander; (3) the rover mission is scientifically interesting on its own merits and also as an element of sample return; and (4) a U.S. rover mission may be more saleable in the current environment because: (a) it should be somewhat less costly than development of sample return vehicle systems, (b) rover operations on the surface of Mars have immediate and extended public appeal, and (c) a rover mission would provide major technological challenges and benefits.

This final report of the preliminary study presents a concise but reasonably detailed discussion of the approach, analyses, results, and recommendations of the study effort. The information presented in the remainder of this report is organized as follows: Section 2 gives an overview description of the MRSR mission scenario. Section 3 discusses the characteristics of candidate sampling sites and reasons for their selection. The key technical issues of the MRSR concept are identified and described in Section 4; these issues include site safety certification, orbiter support roles, landing strategy, lander configuration and rover mobility, and sample control and recovery. The rover mission design analysis, which is presented in Section 5, includes discussion of surface science and sampling operations, rover system concepts, orbiter design concepts, and a comparative summary of the mission options performance.

2. MISSION DEFINITION

The overall mission scenario is shown schematically in Figure 1. Launch operations at Earth are illustrated separately for the rover and sample return vehicle elements. A Shuttle launch with Inertial Upper Stage (IUS) injection of the interplanetary payload is assumed here for the U.S. rover mission; alternatively, an expendable launch vehicle like the Titan IV/Centaur could be employed. The use of the Space Station as a staging base is also possible but not necessary for the rover mission. Our international partner assumes the role of launching and carrying out those mission operations associated with returning the collected samples to Earth. The major functional elements of those operations are the Mars ascent vehicle and the Earth return vehicle. Because the total injected payload in this case is much more massive, possibly beyond the capability of a single launcher in the near term, the diagram depicts a dual launch scenario with assembly of payload elements in low-Earth orbit; the payload elements are then injected onto a single transfer to Mars.

Both the rover and sample return lander systems are launched during the same opportunity window to arrive at Mars within approximately a month of each other. Upon arrival, each vehicle system is inserted into Mars orbit using either all-propulsive or aerocapture techniques. The nominal orbit for the rover system is elliptical with periapsis altitude between 250 and 500 kilometers and a 1-sol orbit period (1 sol = 1 Mars day = 24.6 hours). Orbit inclination will depend on the preselected landing site latitude, among other factors. This choice of orbit allows a dual support role in the rover mission regarding landing site imaging and relay telecommunications. The sample return system may be placed initially into a similar type of orbit.

After a period of coordinated orbital reconnaissance to certify the safety of the preselected landing site (or, if necessary, to choose an alternate site), the two landers are deorbited to enter the martian atmosphere and land on the martian surface in reasonably close proximity. The nominal scenario would have the sample return system landed first, followed shortly by the rover. A reverse scenario is also an option to be considered, especially in a cooperative mode where it may be possible to minimize the separation distance if the second lander could be guided to a radio beacon.

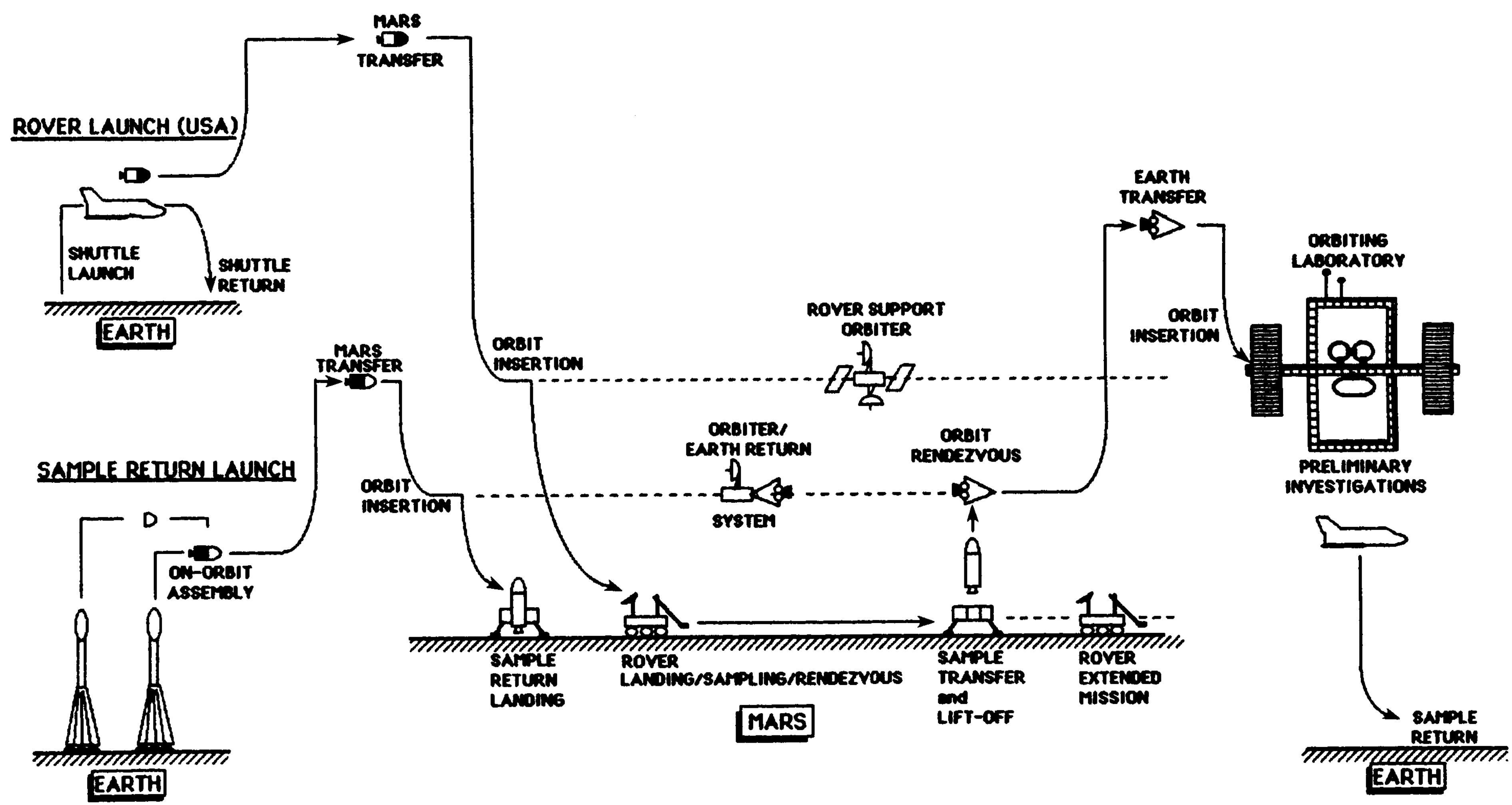

Figure 1. Mars Rover/Sample Return Mission Scenario

The typical stay time on Mars for the conjunction-class flight mode is between 11 and 18 months, depending on the launch year opportunity. When surface science and sampling operations are completed, the rover is directed to rendezvous with the sample return lander and to transfer its sample canister to the Mars ascent vehicle. This operation may be performed only once or in several sorties, depending on such factors as initial separation distance, location of interesting sampling sites, status of the surface environment, and the degree of risk aversion to hardware failure. It is also understood that the sample return lander may have the independent capability of acquiring samples at its landing site and the locally surrounding area. After all collected samples are obtained, the ascent vehicle lifts off the surface and accomplishes rendezvous with the orbiting spacecraft, which includes a separable Earth return vehicle. The sample canister is transferred to this vehicle, which subsequently injects onto an Earth return trajectory. At approach to Earth, a separable capsule containing the sample canister is inserted into orbit and brought to a receiving orbiting laboratory (possibly the Space Station) for preliminary investigations including quarantine protocol testing. The samples are then delivered to facilities on Earth. Specific procedures for the sample recovery phase of the mission were not identified in this study, since such procedures will depend on international agreements which are yet to be established.

Figure 2 illustrates the heliocentric trajectory for the round-trip mission launched in 1996. This is a minimum-energy, conjunction-class flight profile. The Earth-Mars travel time is 302 days, the stay time at Mars is 332 days, and the Mars-Earth travel time is 357 days, for a total of 991 days or 2.7 years. Other launch year opportunities will have varying transfer and stay times, but the round-trip time remains virtually constant at 2.7 to 2.8 years. Figure 3 shows mission timelines for an example sequence of two launches in 1996 and 1998 with Mars arrival occurring during the fall season in the northern hemisphere. Possible dust storm activity could delay surface operations during the early portion of the stay time at Mars; reconnaissance from orbit seems a prudent policy before committing to a landing.

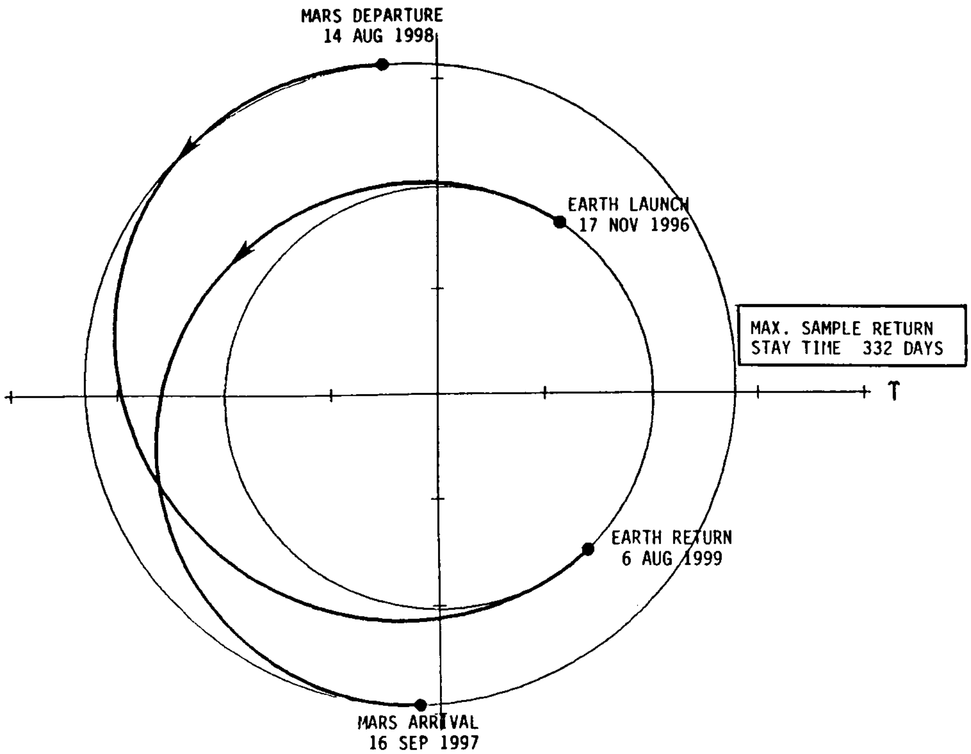

Figure 2. 1996 Conjunction-Class Round-Trip Trajectory

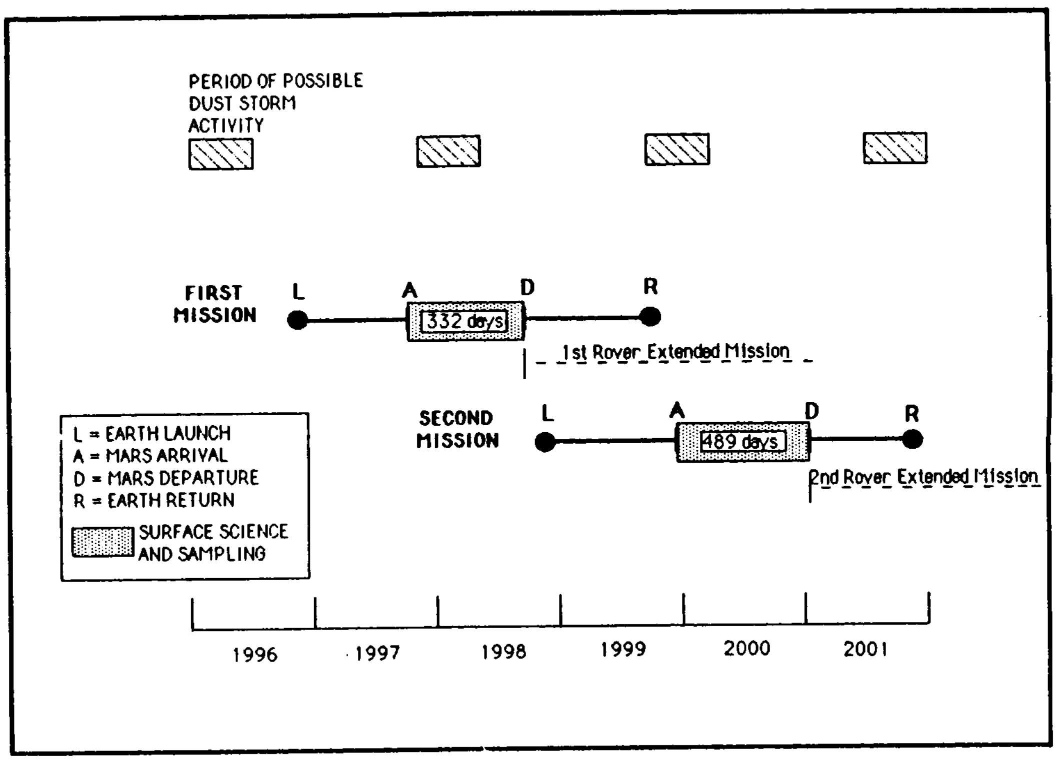

Figure 3. Preliminary Mission Timeline for MRSR

The focus of investigation in this study is the rover mission, given the assumption that this is to be the U.S. role in a cooperative endeavor. The next several sections of this report will describe the characteristics, key design options, and performance requirements of the rover mission concept.

3. CANDIDATE SAMPLING SITES

Terrain studies of candidate landing sites for a future rover/sample return mission to Mars are being conducted to evaluate the geology and surface roughness (trafficability) of each site. An optimum site should have geologic units of widely diverse ages and chemical compositions; the units should occur in close enough proximity and on smooth enough terrain that a roving vehicle capable of traveling no more than about 100 kilometers can collect representative samples. Candidate sites are listed in Table 1; a full geologic map of Mars appears as the frontispiece to this report.

Geologic maps have been compiled at 1:500,000 and 1:2 million scales of the Mangala Valles and Kasei Valles areas and of the Chasma Boreale (north polar) and Planum Australe (south polar) areas. Studies of the topography and surface roughness of the two Mangala Valles sites, using 1:500,000 scale maps as bases, have begun. Geologic mapping has been greatly facilitated by specially enhanced, high-resolution Viking photographs, which clarify stratigraphic relations of previously unrecognized units. Photoclinometric profiles of topographic features (Ref. 3) provide width and depth measurements of four classes of channels, the thickness of some volcanic units, and the throw on some faults. Estimates of the surface roughness of units are being calculated from Viking images, using a newly developed computer program and measurements obtained by T. Thompson of JPL and R. Simpson of Stanford from Earth-based radars at Arecibo and Goldstone, and Viking bistatic radar measurements by L. Tyler and R. Simpson of Stanford.

Studies of the two Mangala Valles sites are virtually complete. A page-size portion of the East Mangala site with proposed traverses is shown in Figure 4. A long, complex geologic history is indicated by the stratigraphic relations shown on the maps and three-dimensional diagrams; crater counts of the geologic units confirm these relations. Crater-density numbers, when compared with the second model of the calibration curve described in Reference 4, indicate that map units range in age from 4.0 to 0.6 Gy. In this area, the ancient cratered terrain of Mars, which may consist of lunar-type anorthosite, norite, and troctolite (ANT suite) or terrestrial-type ancient greenstone-granitoid and granulitic-gneiss terrains (Refs. 5 and 6), is partly covered by

Table 1

CANDIDATE ROVER SITES

Site	Location: Latitude	Longitude	Elevation	Rocks Available
Chasma Boreale	80.8 N	44.0 W	-1 km	Water ice cap, layered deposits, northern plains material
Planum Australe	82.5 S	60.0 W	+4 (?) km	Carbon dioxide ice cap, layered deposits, southern plains material
Memnonia Sulci	9.7 S	174.2 W	+2.5 km	Ancient cratered deposits (possible norites), inter-crater plains, basaltic lava flows, rhyolitic volcaniclastic deposits
Olympus Rupes (Southeast)	13.8 N	131.2 W	+2 km	Basaltic lava flows of three ages
Kasei Valles	15.1 N	75.8 W	+1 km	Intermediate age basalt flows into which channels are incised, and young flows that overlie channels
Mangala Valles				Ancient cratered terrain (possible norites, anorthosites) intermediate-age and -composition lava flows, young basaltic flows, and younger rhyolitic volcaniclastic rocks
West	7.2 S	158.6 W	0 km	
East	4.7 S	147.5 W	0 km	
Elysium Mons	24.3 N	214.8 W	+3 km	Two ages of basaltic flows
Apollinaris Patera	7.5 S	187.2 W	+0.5 km	Two ages of basaltic flows
Nilosyrtis Mensae	35.5 N	302.5 W	+2.8 km	Basaltic intermediate age plains, and ancient heavily cratered uplands
Candor Chasma	10.5 S	74.5 W	+2.5 km	Layered rocks in canyon

a thick sequence of lobate volcanic units, probably basaltic lava flows, and younger, possibly felsic, volcaniclastic rocks. At least three episodes of small-channel formation have been identified and dated. Although many investigators have theorized that most, if not all, martian channels are ancient (Refs. 7-10), our studies show that the small channels appear to range in age as widely as the large outwash channels (Ref. 11). Channels that emerge from the distal end of a lava flow and have leveed banks are probably volcanic in origin; those having tributaries or alluvial deposits at their mouths are probably fluvial.

Enhanced images show some lava flows pouring over a fault scarp, other flows that stop at the scarp, and one flow that appears to be cut by the scarp. Wide, theater-headed channels dissect some of these flows. Fault movement, lava flows, and channel formation can be dated from these geologic relations.

On photoclinometric profiles of a fault scarp that marks the boundary between the southern highlands and the northern low plains east of Mangala Valles, slopes that range from 8° to 25° and throw that ranges from 70 meters to 2 kilometers were measured. Figure 5 shows Viking images that illustrate these relations.

Possible traverses for the rover are also shown on the geologic map of the East Mangala site (Figure 4); samples that may be collected at each stop are shown in Table 2. A core drill that could penetrate surficial desert varnish and weathered rind probably should be used to collect samples.

Ancient degraded channels range in width from 0.7 to 4 kilometers and in depth from 33 to 112 meters; the longest channel is 80 kilometers long. Two branches of the main Mangala Valles system are, where measured, 5 and 4.5 kilometers wide and 200 and 300 meters deep, respectively; their lengths are 80 and 60 kilometers. North-trending, theater-headed channels are 1 to 3 kilometers wide, 100 to 1,500 meters deep, and 6 to 60 kilometers long. Young, narrow channels that lie inside and extend beyond the mouths of theater-headed channels are 300 to 800 meters wide, 20 to 60 meters deep, and

Table 2

EAST MANGALA SITE: POSSIBLE SAMPLES

Station Number	Unit	Description
1	Apl	Young basalt flows
2	Apl	Young basalt flows
3	Apl	Crater ejecta from young basalt flows
4	Apl	Crater ejecta from young basalt flows
5	Hpi	Talus from old basalt flows
6	Hpi	Talus from old basalt flows
7	Hpi	Talus from old basalt flows
8	Apl	Young subjacent basalt flows
9	Apl	Young subjacent basalt flows that cover stream channel
10	AHps	Older basalt cut by stream channel
11	ch	Stream channel deposits
12	AHps	Older basalt cut by stream channel
13	ch	Stream channel deposits
14	Ahw	Talus of older basalt flows
15	Apl	Basalt overlying channel
16	Apl	Basalt flows
17	Apl	Basalt flows
18	Apl	Basalt flows overlying crater
19	Apl	Crater ejecta from Apl and possible older units
20	Hpl (?)	Crater ejecta from large crater; may include ejecta from older units
21	Hpl (?)	Crater ejecta from large crater; may include ejecta from older units
22	Apl	Basalt flows
23	AHps	Older basalt flows
24	Apl	Basalt flows with windblown Apt
25	Apt	Possible young ignimbrites
26	Apl	Basalt flows with windblown Apt
27	AHps	Older basalt flows
28	Apl	Basalt flows

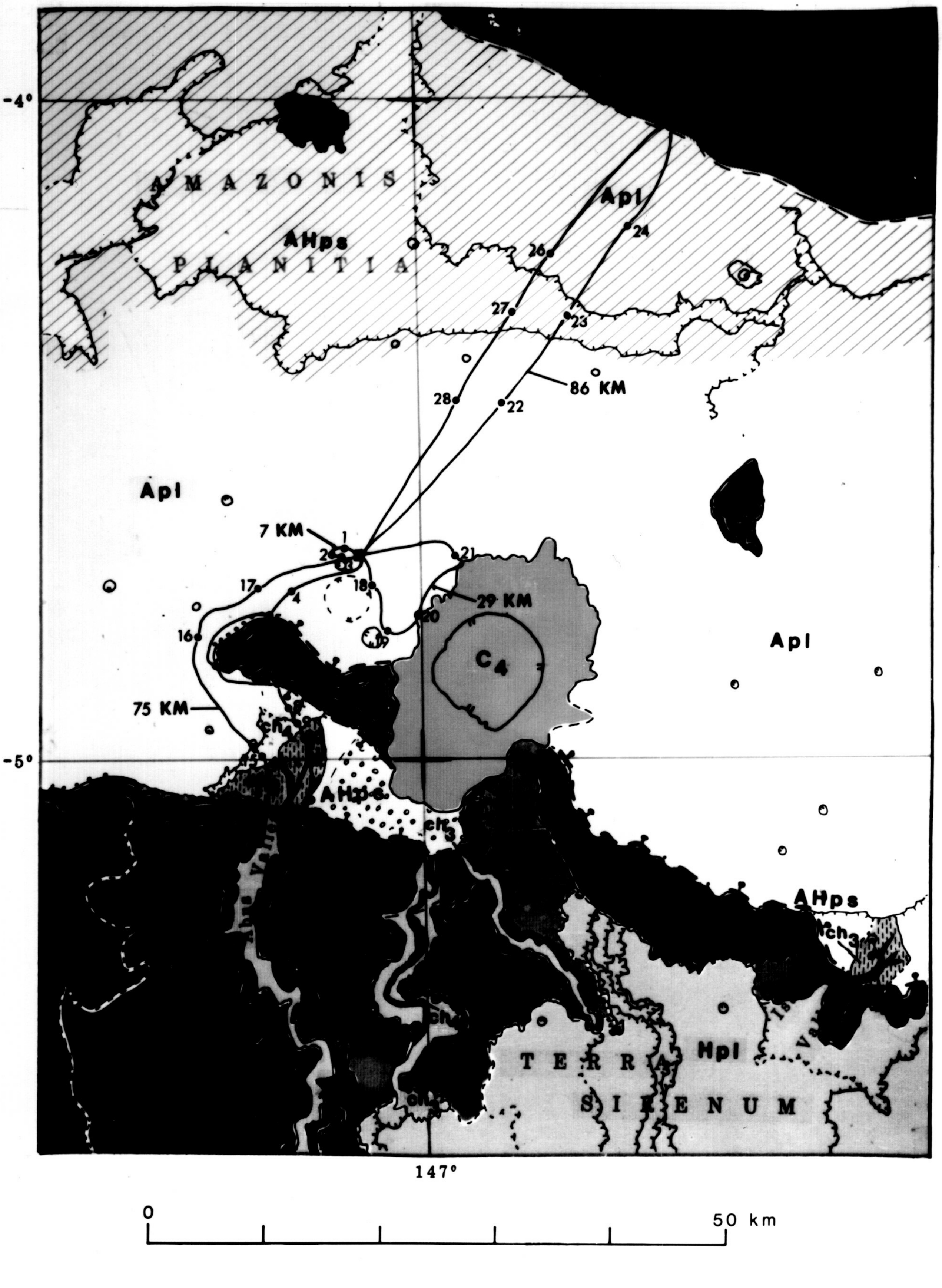

Figure 4. Geologic Map of the East Mangala Landing Site on Mars

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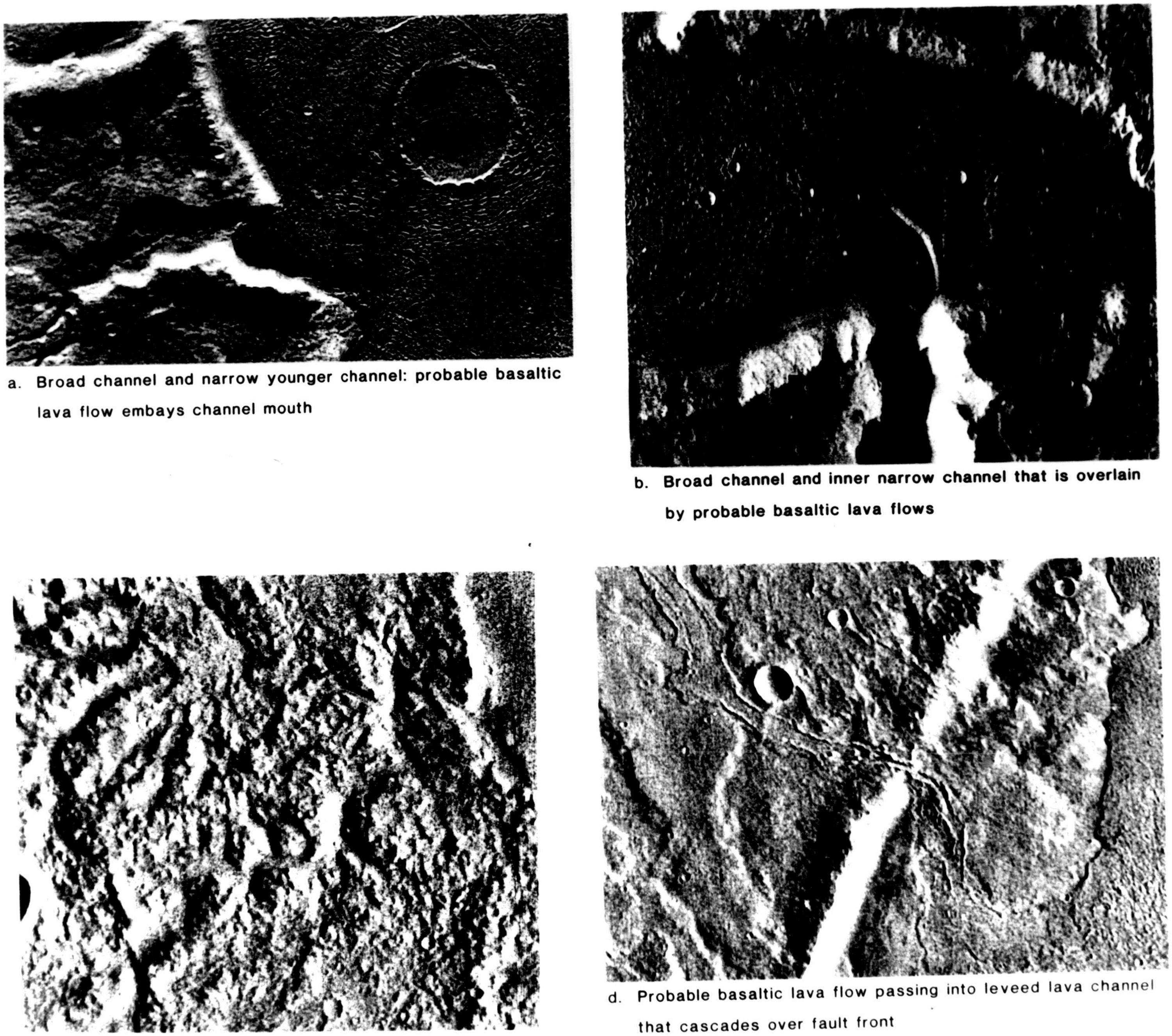

a. Broad channel and narrow younger channel: probable basaltic lava flow embays channel mouth

b. Broad channel and inner narrow channel that is overlain by probable basaltic lava flows

c. Oldest degraded channels

d. Probable basaltic lava flow passing into leveed lava channel that cascades over fault front

Figure 5. Channels on Mars

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20 to 70 kilometers long. Profiles of a possible volcaniclastic unit show it to be about 1 kilometer thick where it embays one crater and spills into another.

At the Kasei Valles site, one geologic map at 1:2 million scale and two geologic maps at 1:500,000 scale have been completed. The site appears smooth on available low-resolution images, but geologic units are more dispersed than at other sites and long traverses would be needed to collect varied samples.

Geologic maps at 1:2 million and 1:500,000 scales of the Chasma Boreale (north polar) and Planum Australe (south polar) areas show deposits of layered ice overlying layered deposits of mixed ice and detritus; young dune deposits are also present. A drill mounted on a rover could obtain meter-thick cores of these layered deposits. These sites also appear to be the smoothest areas on the planet, according to bistatic radar data (Ref. 12) using the Viking orbiter spacecraft and the Stanford radar dish. Samples of ice and rock from the layered terrain should provide a valuable record of the recent history of Mars.

Geologic maps of the Memnonia Sulci and Olympus Rupes sites were prepared earlier on 1:500,000 scale enlargements of 1:1 million scale bases. The Memnonia Sulci area, mapped in 1984 (Ref. 13), displays a wide variety of rock types and compositions, but it lacks the channel deposits found at the nearby Mangala sites. At the Olympus Rupes site, at least three basaltic units that represent stages in the development of Olympus Mons were mapped (Ref. 14). A topographic map of Olympus Mons has been compiled by Sherman Wu and associates, using stereoscopic Viking images. When new 1:500,000-scale bases for these sites are produced, the geologic mapping will be transferred to them.

Most samples that will be collected are expected to be rock _in situ_, rather than the mixed impact debris that was sampled on the Moon. However, there are three sample types that will be valuable even if they are not _in situ_: (1) gravels from stream channels that will provide samples from the stream's entire drainage basin; (2) rocks collected at the foot of a talus slope that will provide samples of layered rocks, otherwise unavailable except by climbing a cliff; and (3) impact ejecta that contain samples of deeply buried material, not otherwise available at the surface.

The Elysium Mons, Candor Chasma, Nilosyrtis Mensae, and Apollinaris Patera sites are being mapped. Three additional sites that contain channels will be selected and mapped.

4. CONCEPT ISSUES

A number of key technical issues associated with the MRSR mission concept emerged during the course of this study. These issues relate to the specific function, operation, and design requirements of various hardware elements of the MRSR vehicle system. A preliminary understanding of these matters is important to their eventual resolution, which may have a significant impact on the performance achievement, development cost, and technical risk of the overall mission concept. The following questions were posed to provide a framework for investigating these issues:

- Site Safety Certification - Given that a fundamental site selection conflict between science and safety exists because the most interesting sites appear to have considerable topographic relief, what are the comparative levels of information affecting the lander design concept and notions of acceptable risk in a certification process?

- Orbiter Support Roles - How does a supporting Mars orbiter enhance or enable extended capabilities of the rover mission in such functional areas as pre-landing site certification, rover traverse planning, and relay telecommunications?

- Landing Strategy - Given that landing accuracy capabilities strongly influence the surface rendezvous operation, which is a unique requirement for separately landed rover and sample return vehicles, which vehicle should land first and how does the targeting strategy affect rover traverse distance requirements?

- Lander Configuration and Rover Mobility - What are the design rationale, alternative options, and evaluation criteria for a lander module that has some degree of tolerance to surface hazards, and for a rover mobility system that can safely traverse terrain of various grades, roughness, and obstacle sizes?

- Sample Control and Recovery - What are the fundamental concerns and design options associated with preservation of volatiles and low-temperature information contained in the returned samples?

These questions are addressed in the discussion that follows.

4.1 Site Safety Certification

The concern about avoiding landing hazards was a major issue during the study. Choosing a safe landing site within an interesting scientific area requires the latest information about the site that can be used to establish the guidance and configuration design of the landing system. The designs discussed below depend on the amount of new information available during the mission.

Site certification relies on two fundamental design assumptions or definitions:

1. Site Certification - There exist, within the entry guidance error ellipse of the landing system, safe touchdown locations of sufficient frequency that the landing system can identify and reach (or be tolerant of) at least one of those sites in the terminal landing phase.

2. Safe Touchdown Location - Safe locations are areas in which the lander design accommodates intact and stable touchdown with an acceptable probability value (to be determined; e.g., 0.9 - 0.99).

There are at least four landing design options, given the above definitions, that depend on the information (I) about the surface characteristics of the landing site available during the landing. The landing system designs will be based upon the new information (ΔI) that will be provided during the mission. Table 3 lists these landing options as a function of the ΔI provided by the landing vehicle and/or the orbiter during the mission. A plus (+) sign is a qualitative representation of a contribution of new information to the process by a vehicle's capability. Note that these options span the spectrum from no new information in the 0, 0 option to vast amounts of new information in the ++, ++ option. The rationale for the selection of these options is discussed below.

Option 1 - Landing Based on Pre-Mission Information. There will exist, prior to the landing system design, a large base of information about the surface of Mars. This information will have been provided by prior missions such as Viking, Phobos, Mars Observer, and Vesta, and by Earth-based radar. It is expected that these data will be low spatial resolution information with

Table 3

LANDING OPTIONS DEPENDING ON NEW INFORMATION (ΔI)

		ΔI_{MRSR}*	
	Option	Lander	Orbiter
Pre-Mission Only	1	0	0
Hazard Identification	2	+	0
Hazard Correlation	3	+	++
Accurate Entry Technology	4	++	++

* ΔI_{MRSR} = New information regarding surface characteristics generated by MRSR mission.

very limited surface coverage at high resolutions (see Ref. 15). This option depends on developing statistical models of the landing sites as follows:

1. The Mars Observer camera will observe scientifically interesting landing sites with sufficient coverage and spatial resolution to assess the local environment of the sites.

2. Statistical models of the landing hazards at the sites will be developed and/or updated from previous data (e.g., Viking) about the site.

3. A landing site will be chosen consistent with the most acceptable statistical model and the lander design will be consistent with this model.

This model is not expected to provide good local terrain estimates at high enough spatial resolutions to allow for landing vehicle designs at a reasonably small scale. Note that there will be no new information provided by either a hazard avoidance system on the lander or new data from the orbiter. Thus, the design would have to accommodate scales of hazards quite large (many meters). This robust design would depend on large structural attributes such as large deployed appendages (air bags, etc.) to land safely within the allowable risk. The risk would probably be lower than that for the Viking lander design, depending upon how robust the MRSR landing vehicle could be made and how carefully the landing site would be chosen. This option results in the most structurally robust landing system design.

Option 2 - Landing Based on Hazard Identification by the Lander. The landing sites would be chosen as in Option 1. New landing site data with sufficient spatial resolution to avoid hazards affecting the landing would be acquired during the landing approach by an instrument onboard the lander. The actual hazards would be identified for the first time during the landing, and propulsive maneuvering would be available to avoid the most dangerous hazards. This option could allow a smaller-scale lander, given an acceptable risk that the terminal guidance capability could, in fact, avoid larger-scale hazardous obstacles identified in real time.

Option 3 - Landing Based on Hazard Correlation by the Lander. This option introduces data taken by a high-resolution imager on an orbiter as part of the MRSR mission. The landing sites would be chosen as in Option 1. However, each landing site would be mapped with high spatial resolution images from the orbiter, providing a map of the actual landing site hazards prior to committing to the landing. Processed orbiter image data of the actual landing site would be stored in the lander memory. During the terminal descent the lander would use image correlation techniques to determine the precise landing location required to safely land the vehicle. Because of the expected additional freedom in selecting this deterministic landing location, the lander scale size could be made smaller than any of the above options while remaining within an acceptable level of mission risk.

Option 4 - Option 3 with Entry Accuracy Enhancement. If a terrain/correlation technique can be used during the entry phase of the landing, very small landing errors would be possible. This last option results in the most sophisticated computational landing system design. The assessment of the risk of this option would be based on the expected reliability of this computational system.

4.2 Orbiter Support Roles

Clearly, the rover is one of the most complex elements of the MRSR mission. In order to minimize its complexity and design risk, it may be beneficial to transfer as many functions as possible to the orbiter. These functions include:

1. High-resolution orbiter imaging to map the landing site prior to landing
2. High-resolution orbiter imaging to map long-range traverse routes (i.e., over the rover's horizon) prior to or during rover operations
3. High-resolution orbiter imaging to locate the sample return vehicle and the rover, assisting the surface rendezvous process
4. An orbiter telecommunications system to relay telemetry from the rover and track the lander during entry and landing
5. An orbiter telecommunications system to relay telemetry (as a backup) during rover operations on the surface
6. Support to the rover/landing vehicle during Earth-Mars transit as well as when the entire flight vehicle is in Mars orbit

Reference 16 describes in detail the requirements that may be expected of a full-capability orbiter support role. The following discussion summarizes several of these support functions.

Landing Site Survey. Prior to committing the descent vehicle to a landing at a specific point on the martian surface, it will be necessary to verify the safety of the site. This will require the assessment of the numbers and kinds of hazards, such as boulders, abrupt topographic changes, or untrafficable surfaces, in a timely fashion so that this information can be used to determine the safety of the potential landing site. The existing data base of Viking and Mariner images of Mars is insufficient to make this assessment. Future data obtained from the Mars Observer and Vesta missions should greatly improve the knowledge base, allowing the pre-mission selection/certification of one (or at most a few) candidate sites, but these data may also prove lacking in spatial and temporal completeness.

Experience from the Viking mission indicates that images on the scale of the descent vehicle which cover the entire area of the lander trajectory dispersion ellipse are required to adequately assess the safety of any potential landing site. This means that meter-scale resolution is required to adequately verify the safety of any potential landing sites for this mission. When considering such factors as the identification of geologic features, it becomes necessary to have sub-meter-sized pixels in order to have an effective meter-scale resolution in the images. Stereoscopic imaging is also needed for landing site validation, but the resolution required for this is lower than that required for monoscopic imaging. It is anticipated that a 1.5-meter pixel size will be adequate for stereoscopic imaging. Navigation analysis indicates that the smallest error ellipse for the descent vehicle trajectory can be approximated by a square 10 kilometers on a side. This is the area that must be imaged during the site validation activity. It is thought that imaging this area in less than ten days would be an acceptable time interval within the mission timeline.

Traverse Route Survey. Although the rover can be navigated across the martian surface without the assistance of orbiter support images, the use of these data will allow a much higher average daily speed for the rover, enabling a semiautonomous mode of operation. The high-resolution orbiter support images will allow long traverses to be planned on Earth, with the rover autonomy and fault protection capabilities used to protect it from small-scale obstructions that would otherwise halt its motion. The use of such images may increase daily traverse distances by a factor of 4 to 5. Additionally, these images can be used to see beyond the rover's horizon, allowing long-range traverse route planning that can ensure that the rover stays within areas that have acceptable trafficability characteristics. This will prevent "back-tracking" to get around areas that are otherwise impassable. Finally, this survey can be used to fine-tune the scientific planning of the traverse routes to ensure that the maximum benefit is obtained from the rover traverses.

The area to be imaged for the traverse route survey will be on the scale of a typical traverse route segment. This will be shorter than the total length to be traversed over the rover mission and longer than the distance traversed in a single day. For planning purposes, a traverse route segment is set equal to an area 25 kilometers long and 2 kilometers wide. The distance of this segment corresponds to the typical straight-line distance that would be traversed en route to a specific objective and the width corresponds to a scale that would allow the rover to maneuver around mid-scale obstructions. The resolution for the images used for this purpose should have the same scale as the rover, i.e., meter-scale resolution. The imaging system used for the landing site survey will be adequate for producing these images. The time necessary to perform this imaging should be short enough that it does not impede the motion of the rover.

Telecommunications Relay. The necessity for and the advantages of an orbiter relay link as a backup or complement to a direct rover-Earth link depend on the landing site latitude and the desired duty cycle of rover mobility operations. For near-equatorial sites, the direct Earth link is available for about 40 percent of each martian day throughout the entire period of surface exploration, except for a few weeks of possible interruption when Mars and Earth are in near-conjunction. The way in which a relay orbiter can extend rover operations is illustrated by Figure 6. This example calculation of Earth and orbiter visibility from the rover assumes the 1996 launch opportunity, a landing site at 6° south latitude, and a 15° elevation limit to account for expected worst-case obscuration by topographic features. The orbiter is located in a 30° inclination orbit with a periapsis altitude of 500 kilometers and a 1-sol period (apoapsis altitude = 33,500 kilometers); Mars oblateness is accounted for in orbit precession where periapsis was initially located over the landing site. In Figure 6, each 90° of local hour angle is equivalent to 6.16 Earth hours. Earth is visible each day for 10.0 to 10.5 hours, almost entirely during daylight conditions at the site. The orbiter is visible around apoapsis for 11 to 12 hours, mostly at night for the first few months and eventually between noon and midnight at mission termination (Mars departure). Thus, if desired, the daytime/nighttime complementary communications link would greatly extend the rover's mobility duty cycle.

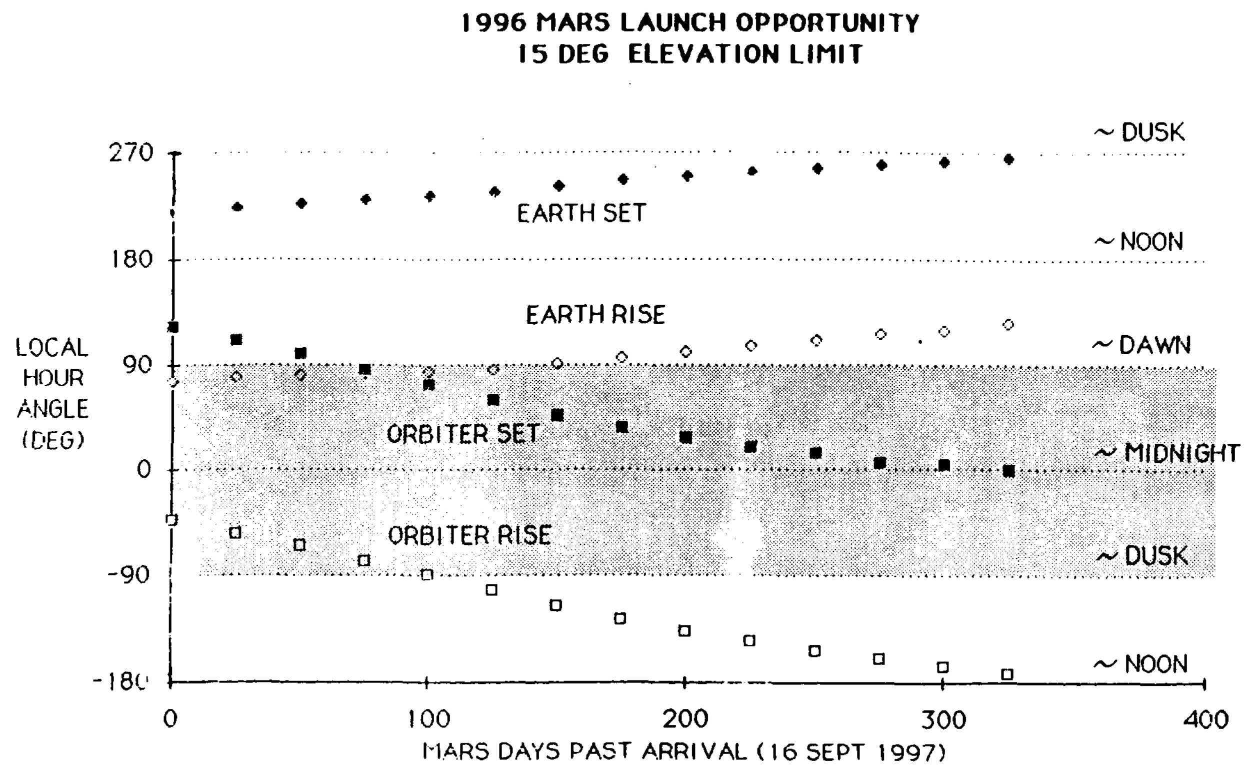

Figure 6. Earth and Orbiter Visibility from Mangala Site (6 Deg South)

The geometry situation is quite different in the case of a polar landing site. Depending on whether it is the north or south polar region, and on the time of year, the direct Earth link may be severely restricted or nonexistent during critical periods of surface operation. An orbital relay link could be crucial to mission success since, at best, the direct link will have only a partial duty cycle over the entire mission. To better understand this inherent problem, an example calculation was made for a landing site at 81° north latitude assuming the 1996 launch opportunity. Since Mars arrival occurs at the beginning of the fall season in the northern hemisphere, Earth is initially visible low on the horizon for slightly more than one month and then is out of view for almost nine months. In contrast, a spacecraft properly located in a 500 kilometers x 1-sol orbit provides a daily visibility period of approximately 22 hours, and thus serves as an enabling communications capability for this mission.

4.3 Landing Strategy

In order to ensure accessibility to landing sites of scientific interest, and to minimize the rover's mobility requirements for rendezvous with the sample return vehicle, it is desirable that the landing errors be as small as can be practically achieved. The landing system definition in this context consists of the aeroshell with its entry guidance capability, parachute deployment at terminal descent conditions, and the lander module with its propulsion and terminal guidance capability. Concerns about landing options involve the determination of landing accuracy measures for different system capabilities, the way in which this information might be used to infer which of the two landers (rover and sample return) should be put down first, and the way the targeting strategy affects rover traverse distance requirements. Analyses of these issues are described below.

Entry Guidance Accuracies. Table 4 lists estimates of the landing error associated with various vehicle types and guidance capabilities. The numbers shown for each case are the lengths of the semimajor and semiminor axes of the error ellipse on the surface of Mars. There are two separate columns of downrange and crossrange numbers. The first assumes that knowledge of the landing site location is not updated following separation from the orbiter. The second assumes that either a beacon or some topographic correlation procedure is used to update the on-board knowledge of the landing site location relative to the lander.

The numbers given for Viking (70s) are taken from a report cited in Reference 17 and reflect the pre-mission predictions. These numbers were obtained by a detailed analysis, and are the most valid numbers that appear in Table 4. The Viking (90s) numbers were extrapolated from the Viking (70s) numbers by factoring in improvements in knowledge resulting from the Viking mission. In other words, if we were to simply repeat the Viking landing, with the same vehicle (L/D = .18) and unguided, the landing error would be reduced. The primary knowledge improvements resulting from Viking, in the present context, were in atmospheric density, the pole location, the surface map, and the rotation period.

Table 4

MARS ENTRY GUIDANCE ACCURACY

Entry Vehicle Type and Guidance Capability	Landing Error (3σ in km) without Beacon DR*	without Beacon CR	with Beacon DR	with Beacon CR
Viking (70s), L/D = .18, unguided	138	53		
Viking (90s), L/D = .18, unguided	76	26	73	25
Low L/D (0.3), Apollo guidance	49	33	25	30
High L/D (1.4), Apollo guidance	18	20	12	18
Low L/D (0.3), advanced guidance	26	31	13	27
High L/D (1.4), advanced guidance	8	8	5	5

* DR = Downrange, CR = Crossrange

The next two rows of numbers are derived from a report cited in Reference 18. Using essentially Apollo guidance, the Mars landing capabilities for a low lift-to-drag ratio (0.3) Apollo-type vehicle and a high lift-to-drag ratio (1.4) biconic vehicle were assessed. The numbers given in Table 4 have been modified from those given in Reference 18 to account for error sources not included (winds, map, pole, and rotation) and to reflect the current knowledge of the atmospheric density. The final two rows of numbers indicate what could be achieved with more capable on-board guidance. Such guidance has not been demonstrated but is currently under development within the JPL Technology Program. The numbers shown in the third and fourth columns indicate that, even with accurate knowledge of the landing site, there are still error sources that keep the downrange and crossrange errors at 5 kilometers or more. These include winds, vehicle aerodynamics, atmospheric density, and the guidance law.

Landing Sequence Options. The principal motivation for landing the rover payload prior to the sample return system is that this option offers the best chance of placing the rover close to an area of high scientific interest. The implicit rationale for the rover-first sequence is that the rover mission would retain control of the science targeting decision, and would not be pressured to land as close as possible to the sample return vehicle, even if the latter were not located in an interesting or accessible science region. On the other hand, the underlying motivation for placing the sample return lander down first is that such a policy provides a deterministic rendezvous point for rover traverse planning. Landing accuracy considerations should help decide which of the two options is the more practical under different conditions.

Figure 7 describes the landing sequence issue as a semi-quantitative selection matrix in terms of the relative landing errors of the two vehicles. A very small error, defined to be within 5 kilometers, will probably be achievable only by a beacon-aided or map correlation guidance scheme. If both landers have this capability, then it is of little concern which one lands first. The science objective motivation argues in favor of the rover landing first if it provides a beacon that can be utilized effectively for close proximity guidance by the sample return lander. In all other cases of unaided guidance, where the sample return landing error is moderately small (5 to 20 kilometers) or moderately large (20 to 50 kilometers), it seems better if the sample return vehicle lands first to establish the deterministic point for surface rendezvous. Note that, perhaps with some nationalistic pride, it is assumed that the U.S. rover lander's intrinsic accuracy (i.e., without beacon support) would always be at least as good as that of our international partner.

Rover Traverse Distance Requirements. A simplified statistical model of landing error characteristics was formulated to obtain a preliminary measure of the rover traverse distances associated with different guidance capabilities and possible landing constraint boundaries near the science area of interest. This relationship between the landing error footprint and rover mobility requirements has not been examined in previous studies. Figure 8

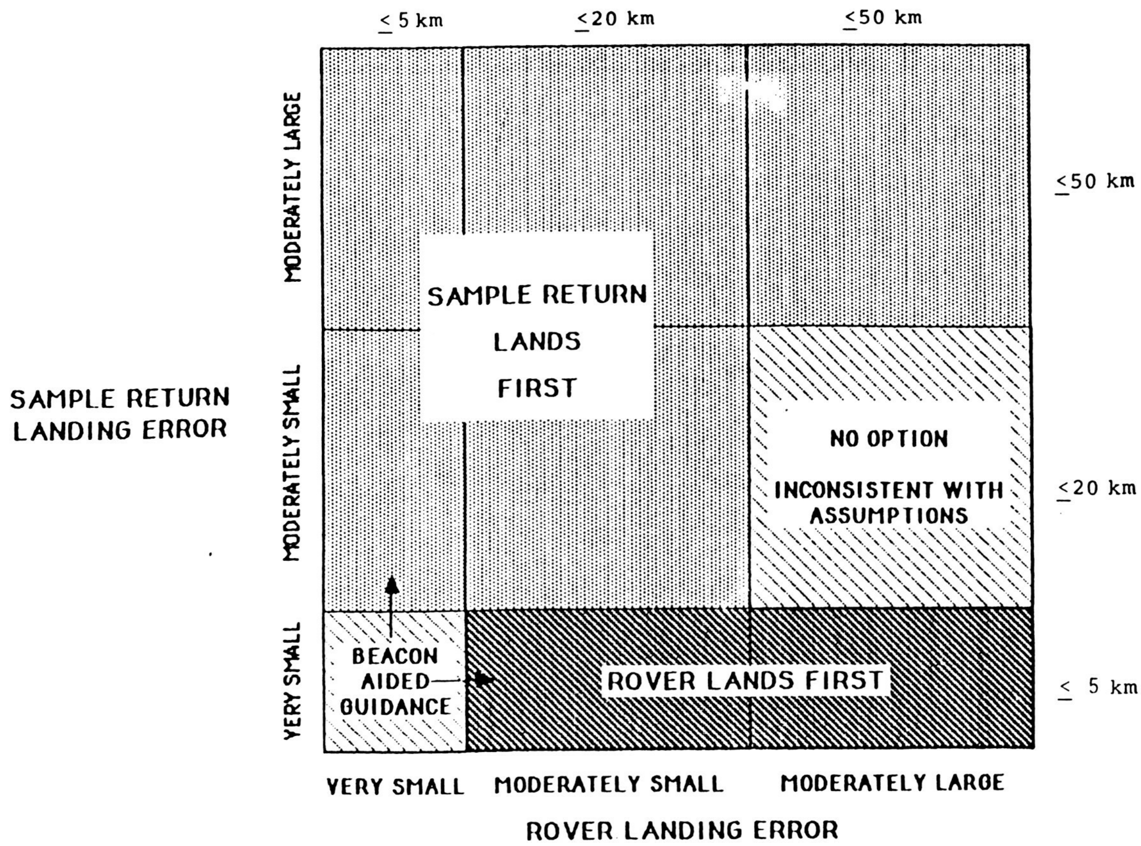

Figure 7. Landing Sequence Options

illustrates the various placements of landing error ellipses considered for this problem. Case 1 represents a targeting strategy where both lander aim points are biased toward a reference site which is arbitrarily placed at the origin of the x-y coordinate axes; the x-axis is taken to be the downrange direction and the y-axis is the crossrange direction. Note that the concept of a reference site is employed only for convenience of the analysis and does not imply that there is only a single "science site" of interest.

If there is no rough terrain constraint boundary, then both landers are aimed at the center of the reference site; otherwise, the error ellipses are placed tangent to the boundary and centered on a line through the site and normal to the boundary. The variables of interest in this simplified model are the displacement, D, between the two landing points, and the traverse, $R_1 + R_2$, from the rover to the site and then to the sample return lander. Not considered here are additional traverses in the vicinity of the reference site, particularly desired entry into the rough terrain region; these could be viewed as deterministic delta distances to be added to the statistical results.

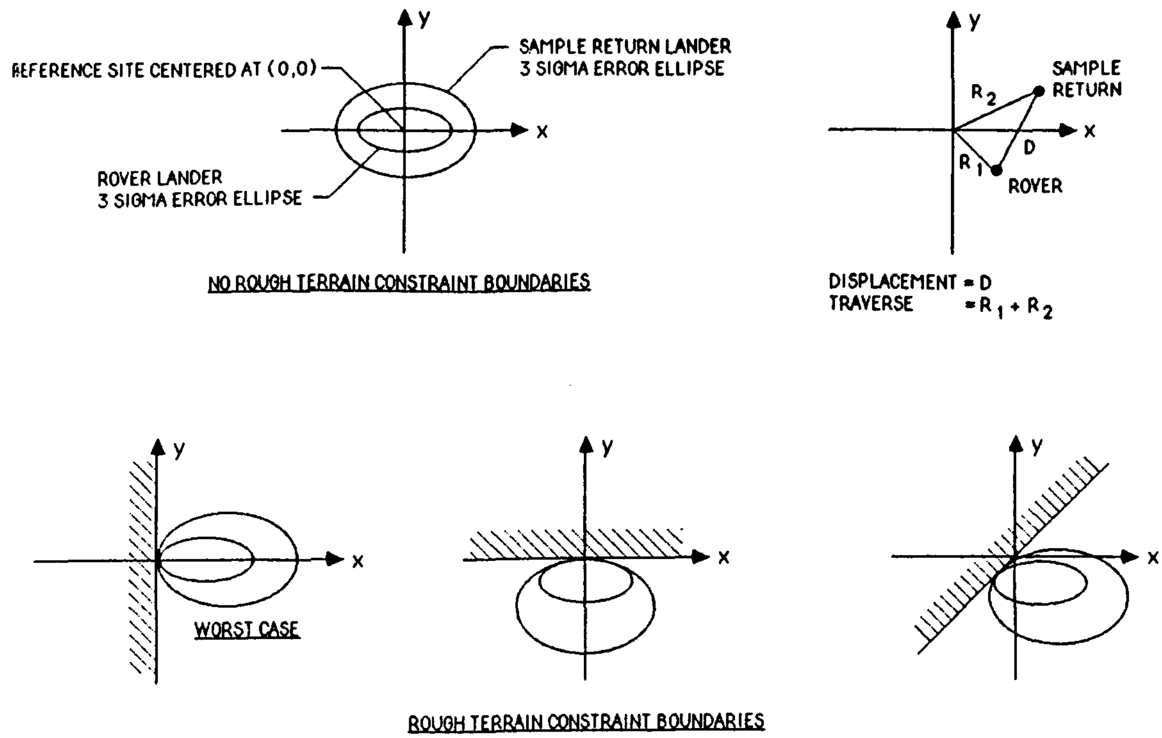

Figure 8. Configuration of Landing Error Ellipse for Statistical Analysis. Case 1: Both Lander Aim Points Biased toward Reference Site

The $R_1 + R_2$ traverse scenario might be thought of as not being overly concerned with risk of rover failure, and one which maximizes the in situ science and sampling objectives. A second scenario, Case 2 (not illustrated), is also postulated wherein the Rover Team is averse to risk and therefore decides to reach the return vehicle as soon as possible with en route samples before exploring the most interesting science areas. The strategy in this case is to land the sample return vehicle first and bias the rover lander's aim point toward the known location of the first lander, still accounting for a constraint boundary that may be in effect. The total rover traverse computed in this case is $D + 2R_2$.

Figures 9 and 10 summarize the results of Monte-Carlo statistical calculations made with a random sampling size of 10,000. The ninety-ninth percentile values of displacement and traverse distances are plotted for several different guidance capabilities of the two landers (see Table 4), with and without terrain boundary constraints, and separately for Case 1 and Case 2 targeting scenarios. These results assume that downrange and crossrange errors are described by independent, zero-mean, Gaussian probability distributions. Also, only the worst-case constraint boundary is shown.

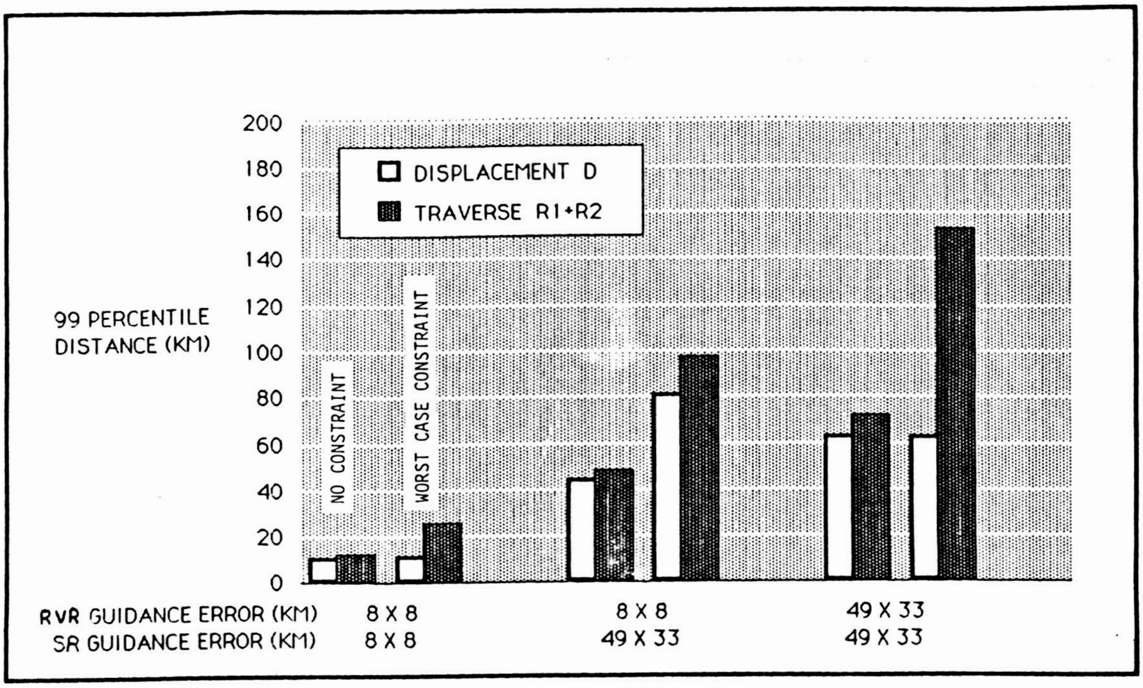

Figure 9. Statistical Results for Lander Displacement and Rover Traverse. Case 1: Lander Aim Points Biased toward Reference Site

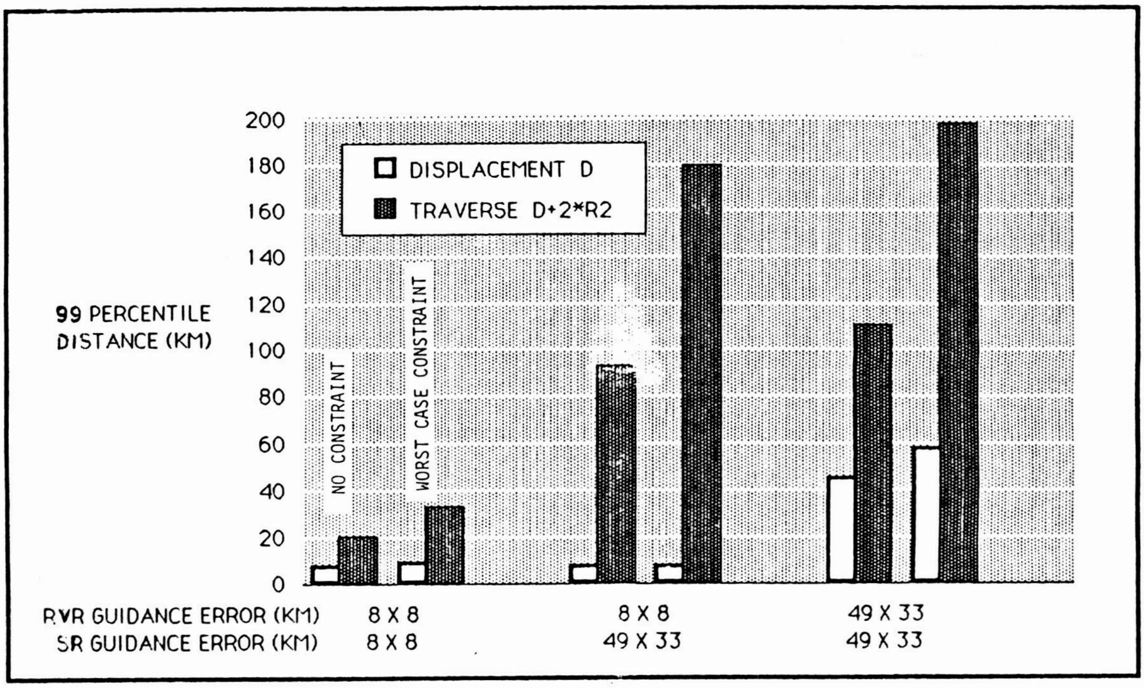

Figure 10. Statistical Results for Lander Displacement and Rover Traverse. Case 2: Rover Aim Point Biased toward Sample Return Lander

Depending on the guidance errors, the displacement distances for Case 1 vary between 12 and 82 kilometers; the constraint boundary affects displacement only when the sample return error ellipse is much larger than the rover lander error ellipse. The $R_1 + R_2$ traverse varies between 13 and 72 kilometers without constraint, but increases significantly to the range of 26 to 154 kilometers when the constraint boundary is present. The adaptive strategy of Case 2 is seen to be quite effective in reducing the displacement distance to between 8 and 58 kilometers. This could be especially important when the sample return landing error relative to that of the rover is large. In this circumstance, the displacement, D, which is equivalent to the rover's direct traverse in sample delivery, is reduced from 45 to only 9 kilometers when no constraint is present or from 82 to 9 kilometers with constraint. The "success" penalty that the risk-averse strategy incurs is that the rover's total traverse requirement, $D + 2R_2$, is increased by as much as 90 percent, and could be as high as 200 kilometers in the worst example of guidance errors. Finally, if both landers have small errors (8 x 8 kilometers) representative of high L/D aeromaneuvering and advanced guidance capabilities, then there is no significant difference between the two targeting strategies and either one would be acceptable.

4.4 Lander Configuration and Rover Mobility

Design issues associated with the terminal landing module and the rover mobility concept are, to some extent, interrelated. The scale of the lander platform depends on the size of the rover it carries, as well as on other factors such as the lander's guidance, propulsion, and the structural subsystems that provide the necessary assurance of hazard avoidance or tolerance. Rover scale depends on its means of mobility as well as on its packaged science/sample acquisition payload and mission-support subsystems. As the rover scale decreases, obstacle avoidance becomes more difficult and mobility control tends to become more complex. Large rover scale, on the other hand, causes mass, power, and packaging to become important design issues. An overarching concern in this entire problem is raised by the fact that the lander system must be packaged inside a Mars entry aeroshell. Therefore, lander size and packaging limitations are likely to be imposed by aeroshell volumetric constraints which, in turn, may be dictated by the maximum payload envelope of the Shuttle cargo bay or alternative launch vehicles. The following paragraphs discuss some of these issues in the general sense of identifying possible options without attempting to baseline any definitive design solution.

Landing Module Configuration. A safe lander design may have to accommodate surface hazards up to 1.5 meters high which may be almost any geometric shape. Robustness of lander structure and mechanisms can take several different forms. The options considered include:

1. An air-bag system with an electronically controlled gas metering to keep the craft level during the energy-absorbing phase of descent

2. A very long-legged design with actuator-articulated joints that provide for the lander to be lowered after coming to rest on the surface

3. Omnidirectional landers that use articulated members to reorient themselves into an upright position after landing

4. A conventional legged design that incorporates dynamically actuated latches on each leg to keep the craft oriented closely to local vertical

5. A conventional legged design without the above latching feature but with a drive-off ramp that is made an intrinsic part of the lander structure prior to deployment on the surface to enhance stiffness and strength

The above designs were given a preliminary overview and evaluated in terms of cost, complexity, weight, technical development, reliability, and stowability. Option 5, shown in Figure 11 as packaged in the Mars entry aeroshell, was found to have the best overall rating.

The benefits of the unlatched, conventional legged design include the following:

1. The concept is made inherently simple and more reliable by utilizing no electronics, electrical relays, or actuators, except for the initial deployment switch and a stored energy device to impart the motion of deployment.

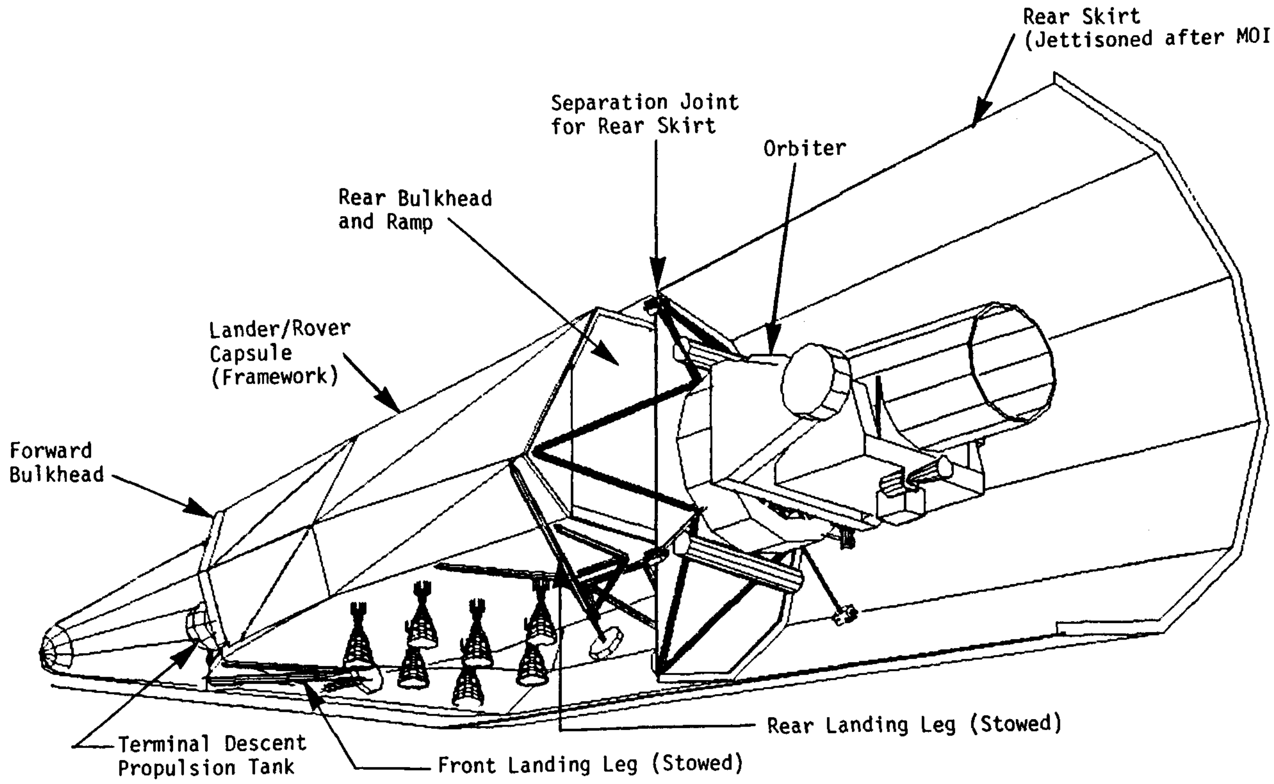

Figure 11. Aeroshell Packaging Configuration of Rover, Lander and Orbiter During MOI

2. A large footprint is possible, thereby contributing to the craft's stability.

3. The simplicity keeps the weight low by reducing the number of redundant structures and devices.

One of the important parameters governing the design of the landing system is the ability to take impact without springing back. Designing the landing system legs to absorb the maximum amount of energy possible in three degrees of freedom and, at the same time, to contribute only a minimum amount to the total craft weight might be done by combining composite materials with energy-absorbing foam matrices that have recently been introduced.

Mobility Concepts. Based on two different scientific sampling philosophies, the two desired alternatives for general mobility are: (1) local controlled mobility, and (2) long-range mobility. Local controlled mobility is characterized by land-roving vehicles (either wheeled or legged) that have relatively precise control over their position and their ability to sample local environments, i.e., to drill into a specific rock or point in the soil. However, their traverse capability is limited due to their relatively low speed and inability to pass over some types of terrain.

Long-range mobility can be accomplished by raising the traveling device above the surface. Traveling in the atmosphere (i.e., a balloon) and only occasionally setting down on the surface is a possibility. Many air traveling vehicles are possible but most are not well suited to sampling operations. An airplane, for example, cannot easily land on and take off from the natural surface of Mars and thus has no effective long-life mobility, as well as having an obvious finite lifetime if it relies on propellant. Balloons have been proposed for long-range mobility but their position cannot be controlled accurately. Also, their payload is inherently limited by the size of the balloon that can be deployed and controlled autonomously on Mars. A compromise between a rover and a balloon might be a blimp that could easily travel over large ranges but under reasonable position control. Its control would have to be precise enough to sample specific locations at each site and to eventually return all of its samples to the sample return vehicle. It remains to be determined whether a blimp would be controllable enough to meet the mission requirements (including a sufficient payload) for the sample return.

In an effort to evaluate these mobility methods, a matrix was developed and is shown in Table 5. Five evaluation criteria are listed across the top of the table. Each entry in the table can have one of three values, ranging from one, representing a good design solution, to three, representing a poor design solution. Note that according to these evaluation criteria, the wheeled rover is the most desirable (lowest total) alternative. Its closest competitor is the blimp, which was penalized most heavily for its inherent mass limitations.

The system configurations which have been considered on a preliminary basis include active and passive wheeled systems with rigid bodies and flexible or intelligent suspensions, articulated wheeled systems with six or eight wheels, looped wheeled systems with four looped wheels with passive and active tread angle control, and legged systems with active control.

Table 5

MOBILITY EVALUATION MATRIX

(1 = good, 2 = acceptable, 3 = poor)

Type	Long Range	Position Control Accuracy	Control Complexity Reliability	Payload Mass	Local Environ. Knowledge	Total	Comments
Wheeled Rover	3	1	1	1	2	8	Range disadvantage
Walking Rover	3	1	3	1	3	11	Complexity issue
Balloon	1	3	2	3	1	10	Control accuracy issue, payload mass limitation
Blimp	1	2	2	3	1	9	Payload mass limitation

Passive systems may show good obstacle-crossing mobility in a preferred direction, but they are very sensitive to approach direction. Reliable algorithms for making this decision autonomously can be developed, but at an additional computational expense. Active systems are much less sensitive to the direction of approach. However, the control of these systems is computationally very intensive and will require considerable computing power. Mobility envelopes based on geometric models have been developed for a number of the candidate systems. Some of these mobility envelopes are included in Reference 19.

Qualitatively, legged locomotion offers better grade-climbing ability than either wheeled or tracked vehicle types. However, the computational complexity could be a major development problem. The bulky and complex mechanisms necessary for legged locomotion are likely to carry a considerable weight penalty compared to some of the other options. Thus, it was anticipated that the most capable mobility systems are also likely to be somewhat heavier than the less capable systems. However, a scaling analysis was performed and the results showed that this was not the case.

Selection of the optimum mobility system will require close study of projected mission profiles in terms of projected terrain types, payload to be carried, and overall system weight constraints.

4.5 Sample Control and Recovery

The overriding objective of this mission is to return a suite of martian samples to Earth for detailed intensive study. The requirement is that the samples be preserved in a way that retains their martian information to the maximum extent possible. The primary concerns are the information associated with the volatiles (and possibly their ices) and the subtle information associated with low-temperature degradations and transformations within the samples of rocks, soils, and ices. These types of information are critical to studies of past and present climate and the possibility of martian life-forms.

There are two fundamental options for preservation conditions:

- "Cold" samples with volatiles retained
- "Warm" samples with volatiles lost (in fact, intentionally extracted)

All other things being equal, there is little argument that a cold, volatile-laden sample provides the most information and the highest quality information. However, all other things are not equal, and the technical feasibility and cost of returning the samples cold must be assessed.

The concern for the preservation conditions for the samples extends through several aspects of the mission. Issues include:

- Trauma to the sample introduced by the sampling tools
- Sample storage conditions while on the martian surface

- Sample storage conditions while in transit from Mars to Earth
- Thermal protection for the samples upon arriving at Earth

Preliminary thermal modeling (Ref. 20) of a coring sampling tool indicates that rocks, soils, and water ice can be sampled using a coring drill with very small increases in the internal temperature of the materials being drilled. The drilling sampler was modeled as the worst case (for heating the sample) of all sampling tools under consideration. The parameters modeled were the specific energy required to cut through the substrate of interest, the heat capacity of the substrate, and the thermal conductivity of the substrate. Various characteristics of the drilling tools were tested, including penetration rate and conductivity of the drill materials.

Although the results are preliminary, it is evident that even this "worst case" type of sampling induces only small temperature changes within the sample. The most severe case is the coring of a basalt. Using a 1-centimeter diameter core, the interior temperature of the sample is raised only about 10 K, while the exterior of the sampled core may be heated to a temperature about 100 K higher than the assumed ambient temperature of 215 K. Most information preserved in a martian basalt sample will survive these types of heating. Similar modeling of the same coring device into a dry martian soil results in only an 8 K temperature rise at the exterior of the core and less than 1 K temperature change in the core's interior. In the modeling, the addition of water ice to the martian soil results in even smaller changes in temperature due to the increased thermal conductivity and higher heat capacity of the mixture. The most heat-sensitive information is expected to be found in the soils (ices, clathrate compounds, adsorbed gases, etc.). While these modeling results are encouraging, they must be confirmed by actual testing measurements, a topic for continued study.

Sample storage will probably require some type of cooling capability on the rover and perhaps in the Mars ascent vehicle. These areas have not been defined in this study. There is power available, and the ambient temperature on Mars is near the temperature needed for preservation (<260 K?); therefore, there have been no technical issues raised to question the ability to keep the samples cold on the rover. More definitive engineering confirmation of this belief can be done when specific rover systems and specific sample temperature requirements are better defined.

Preserving the samples in a cold condition in the return spacecraft was studied as part of the 1984 Mars Sample Return mission study (Ref. 2). That study concluded that the spacecraft should be able to maintain temperatures in the range of 240 to 250 K by passive cooling alone. The short engineering study considered a generic spacecraft in the form of a right cylinder. In that simplified configuration, little more than an appropriately radiative paint on the spacecraft provided enough cooling to maintain the required temperature. Clearly, as the return spacecraft becomes better defined, this study will have to be repeated at a more detailed level. In the absence of a more definitive study, this preservation problem seems to be solvable.

The largest thermal threat identified for the returning samples is the heating of the return spacecraft as it orbits Earth. The infrared radiation from Earth is the most difficult heat source with which to contend. The problem would be aggravated by the heat pulse generated by aerocapture of the returning vehicle in Earth's atmosphere prior to going into Earth orbit. Again, the study of this problem has been restrained by the lack of specifics with respect to the design of the return spacecraft and even by the uncertainty of whether aerocapture will be the means of decelerating the vehicle for its rendezvous with Earth.

In another recent study (Ref. 21), the question of rapid recovery of a returning planetary sample spacecraft was investigated. One conclusion of the study was that a spacecraft in circular, low-Earth orbit can be recovered in less than ten hours with a rendezvous vehicle in the OMV (Orbital Maneuvering Vehicle) class. If the spacecraft were placed in a highly elliptical orbit, which would cause it to spend much less time near the warm Earth, the rendezvous can still be accomplished in less than two periods of that orbit. The performance cost of elliptical recovery is that it requires a rendezvous vehicle in the Centaur or OTV (Orbital Transfer Vehicle) class.

The overall conclusion of the studies to date is that the martian samples can be returned to Earth in a cold state. However, the solutions to the various problems are preliminary and are piecewise solutions to a problem that must be looked at from an overall systems point of view. For the moment at least, cold sample return seems to be technically feasible, but the technical costs must be weighed against the incremental information retention in the returned samples. How much is the information in cold martian samples worth? Is a Mars Sample Return mission that brings back only warm samples worth the trip? The answers to these questions await the careful attention of the science community.

5. MISSION DESIGN ANALYSIS

This section presents more detailed information about several important aspects of the rover mission design. These subjects include sampling and surface science operations, rover system concepts, orbiter design concepts, and an integrated summary of mission options performance including mass statements. Although there has been no intention in this preliminary study to specify a baseline design, it was necessary to derive plausible designs in order to assess the technical feasibility of the rover mission.

5.1 Sampling and Surface Science Operations

The science strategy for Mars surface and sample science has been in place for a decade. After the Viking mission, several committees of the Space Science Board (SSB) of the National Academy of Sciences studied the next steps in Mars exploration. The conclusions of those studies have stood unchanged. The objectives for intensive study of Mars are: (1) chemical, mineralogical, and petrological characterization of a range of samples; (2) determination of the nature and chronology of the martian surface-forming processes; and (3) determination of the distribution, abundances, sinks, and sources of volatiles, including study of both past and present biological potential.

The MRSR mission combines aspects of both the sample return objectives and the on-surface exploration objectives of previously studied mission concepts (Ref. 22). For purposes of this study, we assumed the following set of science objectives:

1. The mission must be successful scientifically both as a sample return mission and as a surface science mission.

2. The mission should sample a wide variety of surface materials.

3. The mission should visit multiple terranes if possible.

4. The mission should return an intelligently selected suite of samples (grab sample is not an adequate return on investment).

5. The rover should have sample characterization capability.

6. The mission should sample the atmosphere.

7. Both weathered and fresh samples should be collected.

8. Sampling and sample preservation should be performed at near-Mars conditions.

9. Several kilograms of samples should be returned.

10. Extended mission capability for the rover is assumed.

Martian Sample Suite and Tools. The martian samples chosen for return to Earth will be selected carefully on the basis of their importance to the scientific problems that they will enlighten. Similar scientific arguments will be made for the choice of the landing area to be visited, and certainly the sample suite will reflect the priorities of the science problems available at the site finally chosen.

It is useful to discuss the suite of samples that might be returned from the surface of Mars in terms of their functional impact on the sampling system. Table 6 describes a possible sample suite.

Table 6

MARTIAN SAMPLE SUITE

In-place rocks	Cannot pick up
Hand specimens	Can pick up
Pebbles	Small, whole samples
Surface soils	Few mm and smaller
Subsurface soils	Several meters deep
Ices and volatiles	Probably mixed with soils
Atmosphere	
Atmospheric dust	

This study was concerned primarily with the rock and soil sampling strategies. It was assumed that the dust and atmospheric collectors were self-contained systems and that their designs could be carried out independently of the main sampling and preservation system design, at least in this early stage of the planning activity.

The specific strategy for selecting samples will depend on several factors. The need for each type of sample will be evaluated for its scientific usefulness. The relative number of rocks and soils available will depend both on the pre-mission plan for the landing site chosen and on the mission mode decisions made based on what is learned about the site after arriving and starting to collect information from the rover science systems.

Table 7 lists the kinds of tools needed to recover each type of sample functionally defined above.

Table 7

SAMPLING TOOLS

Type of Sample	Sampling Tools	Subsampling Tools
In-place rocks	Chipper, core drill	Minidrill, rock breaker
Hand specimens	Robotic arm/hand	Minidrill, rock breaker
Pebbles	Robotic arm/rake	None
Surface soils	Scoop, drive tube	None
Subsurface soils	Coring drill	Core saw, minicorer
Ices and volatiles	Coring drill (cold)	Volatile trap
Atmosphere	Bottle, molecular sieve	None
Atmospheric dust	Dust collectors	None

Finally, the issues of how many samples to return and how much mass is sufficient affect the design of the sampling system. The mission will return a limited amount of samples, probably about 5 kilograms. One mission objective is to obtain the greatest diversity of samples. There is a natural conflict between these requirements, especially if areas of Mars are as richly diverse as it is hoped. The evaluation of trade-offs within this mass versus diversity problem is the topic of studies that will be undertaken in the near future.

The third column of Table 7 lists tools which take smaller samples from the larger samples initially acquired by the sampling system. This is one approach to maximizing diversity while not exceeding the mass limitations of the return vehicle. Probably the most illustrative example of this subsampling strategy is the case of obtaining soil cores. By taking a small amount of material from a number of depths in the core stem, the range of materials encountered as a function of depth can be recovered without taxing the return mission with the full mass of the intact core.

Sampling and subsampling systems will add complexity to the mechanical and control design of the rover system. It is presumed that there will be some independent sampling capability on the return vehicle as well, adding complexity to the vehicle design. An additional source of complexity is the interaction of the sampling systems with the on-board analytical instruments. We will continue to define and evaluate the future benefits of our improved knowledge from surface-generated data and from an increasingly diverse set of returned materials, and then assess these benefits against the increasingly complex systems required to provide them.

On-Surface Science Capability. The rover must have on-board instrumentation which collectively allows: (1) traverse planning, rover movement, and site documentation; (2) sample characterization, selection, and documentation; (3) data provision of sufficient import to constitute a mission without sample return; and (4) the measurement of properties or conditions that are unlikely to survive sample return, or that are transient or local. Mineral phases stable only at Mars ambient conditions, volatile exchange between soil and atmosphere, and local weather phenomena are examples of this last point.

An instrument set capable of satisfying these criteria consists of the following general instrument types:

1. Imager
2. Elemental analyzer
3. Water analyzer
4. Atmospheric and evolved gas analyzer
5. Mineralogy characterizer

Imager: The imaging device is the rover's most important instrument. The imager must be capable of long- to short-range focus and must be stereoscopic. Resolution requirements vary with distance, on the order of centimeters or less for long range and on the order of a millimeter for short range. High magnifications for sample characterization (at scales of 40X or more, for example) are not required, but the provision of a lens of approximately 10X would allow discrimination of textures, mineral grains, and particulates of submillimeter dimensions, sufficient for identifying most rock types, including volcanics. Textural characterization (is a particular sample an igneous rock or not?) may prove to be particularly useful in sample selection decisions. A vital role of the imager is to link local surface morphology and materials to larger-scale contexts such as geologic map units. The imaging system should be multispectral with reflectance spectrometer capabilities to correlate local materials to similar regions identified from orbit. A multispectral capability is also important in making rover traverse decisions and in sample discrimination and selection because it provides unit and rock type characterization, on a relative basis, if not absolutely. A multispectral capability complements elemental analyses and allows extrapolation over large areas.

Elemental analyzer: Determination of the bulk composition of rocks and soils is required for developing a real-time sample selection strategy and for using the rover as a mapping tool. Chemical composition (plus textural data) provides the basis for classifying rocks and soils, and is fundamental in deciding what to sample. Classification may require measuring percent levels of major elements (e.g., silicon, magnesium, iron, and alkalis), light elements (e.g., carbon and nitrogen) and trace elements such as the halogens, sulfur, uranium, and thorium. In addition to classifying materials analyzed, elemental analysis calibrates imagery data, allowing an inexact but useful extrapolation of elemental compositions on the basis of remote reflectance measurements. Elemental analyzers which use radioactive sources to excite target materials producing alpha particles, protons, X rays, and gamma rays are possible candidates for rover-mounted elemental analyzers. Such analyzers are capable of satisfactory sensitivity for the major rockforming elements as well as uranium, potassium, thorium, and some light elements. Accuracy is generally sufficient to classify rock and soil types. The length of time required for a complete analysis may be a disadvantage.

Water analyzer: A primary objective for a sample return mission is the collection of ices, presumably primarily, if not exclusively, water ice. The principal sampling mode is likely to be a drill which cores the martian regolith to some depth. Such an operation is time consuming; consequently, it is important to know before drilling if ices are present at the surface or are likely to be present beneath the surface. It is improbable that such a determination could be made via imagery or by efficiently using elemental analysis techniques. Electrolytic cells mounted on soil and/or rock samplers, however, represent one possible approach, offering the virtue of simplicity with low weight and power requirements.

Atmospheric and evolved gas analyzer: Viking data on the composition of the martian atmosphere were crucial in studies concerning the martian origin of the SNC meteorites; this situation illustrates the value of fundamental measurements. The questions of whether or not the composition of the atmosphere will have changed since the Viking measurements or if changes occur during rover traverses (e.g., diurnally or seasonally) are fundamental. In addition, an atmospheric and evolved gas analyzer can be effectively coupled with a differential scanning calorimeter/sample heater to measure volatiles driven from low-temperature minerals and ices during calorimetric analyses. Biologic potential can probably be most accurately assessed with the atmospheric and evolved gas analyzer.

Mineral characterizer: Unlike the surface of the Moon, the martian surface is chemically active. Martian rock and soil surfaces include an array of weathering and alteration products plus low-temperature precipitates, including ices. It is largely unknown what mineral species are present, but Viking data indicate that volatile-bearing species are important and that they are unstable at elevated temperatures. These predominantly surface products may reflect martian ambient conditions such as atmospheric pressure, gas partial pressures, temperature, and the presence or absence of volatiles, and they represent an important climatological record. In addition, weathering and alteration products affect spectral properties. The presence or absence of volatiles may be important in recognizing areas of biologic potential. Sampling these low-temperature mineral suites and determining when volatiles are present are important objectives. The rover should have suitable onboard devices for these operations. Differential scanning calorimeters (which may be coupled with evolved gas analyzers) are commonly used to characterize species which undergo changes (e.g., volatile loss) upon heating, and they represent one effective way to characterize low-temperature species.

5.2 Rover System Concepts

There are two extremes of design philosophy for a complex system such as the rover. One philosophy would promote utilization of the highest technology level expected to be available during the development era of the rover. This philosophy would yield the most complex and sophisticated capability, as well as the highest development cost and design risk. A more conservative philosophy would depend on the utilization of near state-of-the-art technology that accomplishes reasonable goals but at the sacrifice of sophistication. This philosophy would result in lower development cost and a more robust design with lower risk, but with capability and mass performance penalties.

Design Rationale and Requirements. A fundamental goal of this study was to establish feasibility for a near-term mission. The more conservative design philosophy was used to meet that goal. A key manifestation of this philosophy was the establishment of a scale size for the flight vehicle system

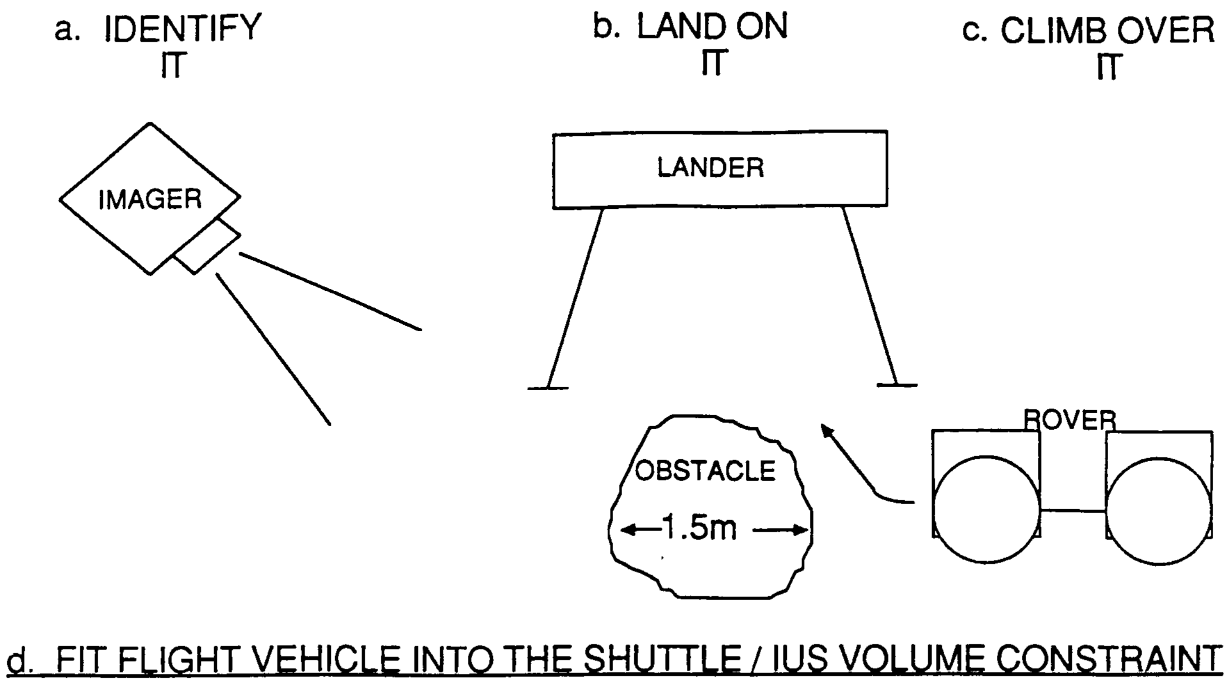

Figure 12. Rover Design Scale Related to Obstacle

design. The scale was based on the size of obstacles on the surface of Mars that the systems must negotiate.

There exists a number that is the diameter (or some other dimension) of an obstacle which determines the scale size of all rover-related systems. The number affects the capabilities of the systems in the following areas:

a. Orbiter imaging resolution capability
b. Landing module hazard avoidance capability
c. Rover long-range-traverse hazard avoidance capability
d. Launch and flight vehicle mass and volume capability

For this study, we have chosen a value for this number of 1.5 meters. Clearly, a parametric analysis of the design complexity and cost implications of this scale value must be done in future studies. Figure 12 illustrates the relationship of the 1.5-meter design scale to each of the system elements identified above.

A complete set of functional design requirements consistent with the scale size of the current design can be found in Reference 16. These requirements may be summarized as follows:

1. The rover mass including science payload shall be less than 700 kilograms.

2. The rover volume during transit shall be consistent with a rover/lander stowed configuration that can be packaged within a right-circular conical segment 6 meters long, with a 3-meter diameter base, and a 2-meter diameter top surface.

3. The traverse rate on the surface of Mars shall be 1 kilometer per day.

4. The rover shall surmount obstacles of 1.5 meters.

5. The rover shall climb grades of up to 35% on loose sand.

6. The rover shall have a maximum telemetry rate of 30 kbps for mobility control purposes.

The rationale for these requirements was identified during the study; a more detailed discussion can be found in Reference 16.

Rover System Design and Configuration. The system design relies on minimum extrapolation of current design concepts for roving vehicles. A multi-wheeled rover was chosen for its reasonably well-known performance capability in many environments. A multi-cab design allows an ordered packaging of each rover subsystem in addition to having known good mobility performance. Thermal control on the deployed rover was a key study issue. Multi-cab rovers had apparently been dismissed in the past in favor of single cab designs because the rover subsystems had to rely on heat transfer from the Radioisotope Thermoelectric Generators (RTGs) into the cab. The solution in the current design is to provide Radioisotope Heating Unit (RHU) modules for each of the cabs.

The rover configuration shown in Figure 13 contains three cabs, each with two independently powered 1.0-meter diameter wheels, connected by passive axial flexural ties which permit yaw, pitch, and roll motions. The rover is

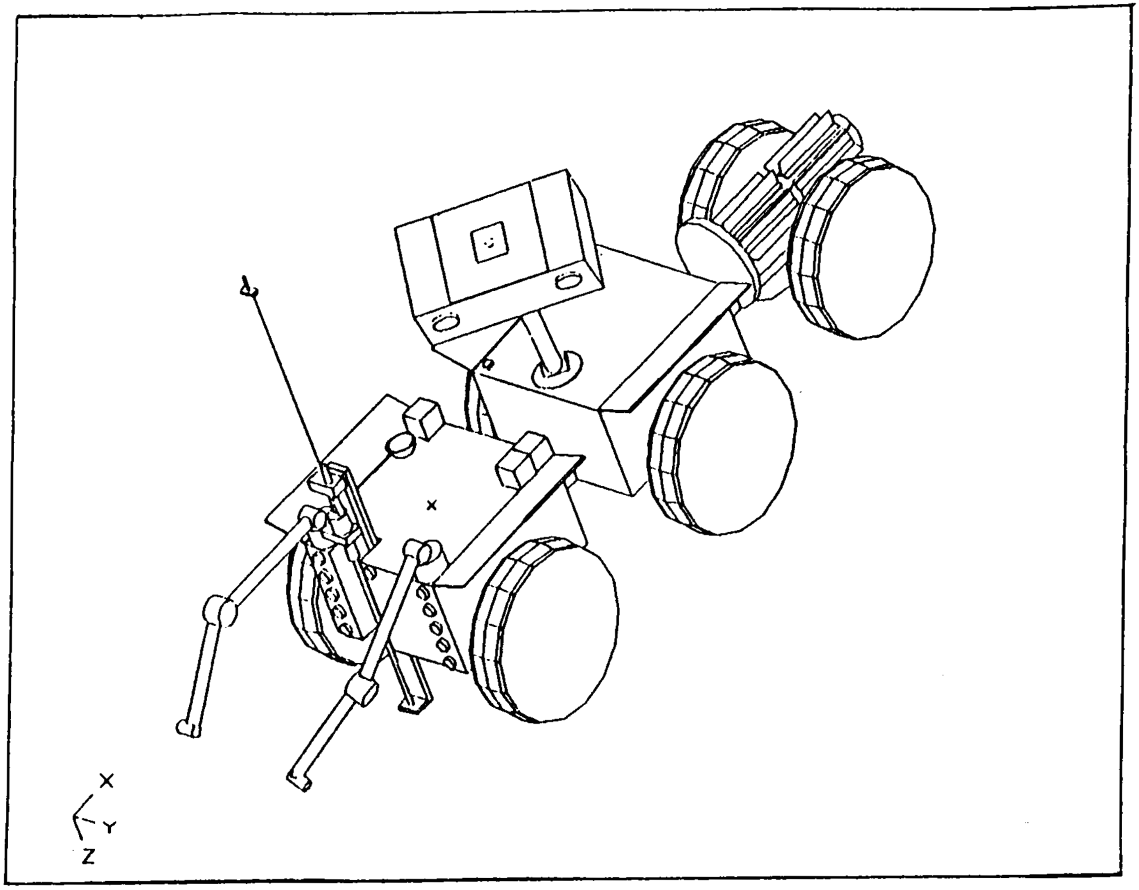

Figure 13. Mars Rover Deployed Configuration Concept

steered by counter rotation of the two end cabs about the junction of the axial tie and the individual cabs. The rover axle spacing is 1.6 meters to allow surmounting a 1.5-meter obstacle. This results in an excessive length for the rover when it is stowed in the aeroshell. Therefore, the passive axial flexural ties must collapse roughly 0.3 meters each in length when the rover is stowed.

The front cab contains the surface sample science, including the drill mechanism and the two robot arms. The drill mechanism folds back over the top of the front cab and is rotated into a vertical orientation for use. It fits into a pocket in the front of the cab in order to not protrude in front of the cab. The drill could be used to make holes at various slant angles by not rotating to the full vertical position. The drill-feed mechanism is mounted on a slide so that the drill can be raised until it is flush with the bottom of the cab to provide maximum ground clearance.

Effector mechanisms to be used by the robot arms are stored on the front face of the front cab and are assumed to be attachable to the arms by a bayonet feature. The robot arms stow folded back on top of the front cab. A strobe light is depicted as centered at the top front of the cab. The surface specimens would be distributed to various science instruments in the front cab by effector "hands" on the robot arms. The specimens could be those gathered by the arms or raised by the drill mechanism.

The middle cab contains the communication, power conditioning and storage, control, and navigation subsystems. No surface specimen related science could be mounted in or on the center cab. The vision system for navigation is mounted on a three-degree-of-freedom mast. The base of the mast can rotate in azimuth and elevation while the camera head can nod. The camera head contains two cameras to provide the stereo pair images. The antenna arrays are mounted on top of the camera head to take advantage of the mast-aiming capabilities to direct the antenna beam.

Radiator plates are mounted over both wheels of the front and center cabs to dissipate excess heat. The radiators are canted 15 degrees up from horizontal to assist the condensate in the heat pipes to return to the evaporator sections of the heat pipes. This configuration minimally obstructs the vision system and the robot arms. The rear cab carries the RTG assemblies used to provide rover power. A radiation shield is shown adjacent to the RTG to reduce the radiation exposure in the rest of the rover.

A mass and power estimate for the major subsystems of the preliminary rover design is given in Table 8. Included is a science payload weighing 90 kilograms and comprised of candidate instruments of the type discussed in Section 5.1. Note that the RTGs supply power for either mobility or telecommunications, but not both simultaneously. Also, batteries supply power for high amperage tools such as drills and arms.

Rover Mobility Guidance and Control. There are two teleoperation methods considered in this design concept. The first, defined as the Computer-Aided Remote Driving (CARD) method, relies only on images acquired by the rover's

Table 8

MASS AND POWER ESTIMATE FOR PRELIMINARY ROVER DESIGN

Subsystem	Mass (kg)	Power (watts)
Structure	69.0	---
Telecommunications	30.1	30.0 (132.0)*
Power	76.1	10.0
Command and data	20.0	18.0
Locomotion and control	73.2	120.8 (18.8)*
Cabling	24.0	---
Thermal control	18.0	---
Mechanical devices	15.3	8.0
Data storage	17.8	18.0
Sample acquisition/processing	118.0	12.0**
Science instruments	90.0	20.0
Subtotal	551.5	236.8
Contingency	55.0	
Rover total	**606.5**	

* Power listed is for rover traverse/data record mode; parenthetical values are for data transmit/playback mode of operation.
** Battery power is used for high amperage tools such as drills and arms.

stereo-camera system to designate an extended path up to 250 meters long using an Earth-based image analysis and computation technique. The rover moves over this range during each command cycle with Earth as described in detail in Reference 16. The range of each interval is limited by the on-board imaging capability.

Another technique, defined in Reference 16 as semiautonomous, allows longer range traverses during a single command cycle and relies on the availability of high-resolution imaging from an orbiter. These orbiter images can be processed on Earth and a capability similar to the CARD computations can plan a much longer traverse, avoiding objects that are resolvable in the

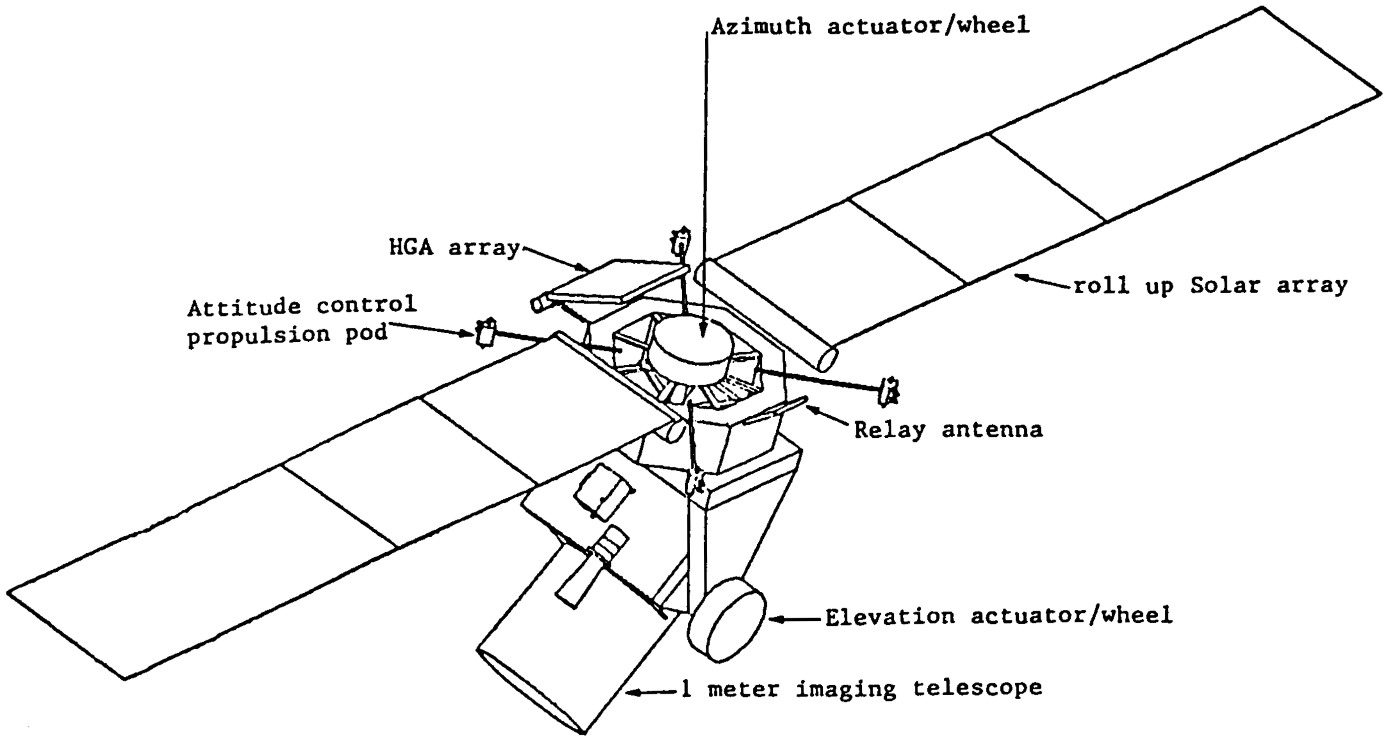

Figure 14. Multi-Purpose Orbiter Configuration Supporting the Mars Rover

orbiter images. The semiautonomous method can result in an average rate of travel of about 10 kilometers per day.

5.3 Orbiter Design Concepts

Two supporting orbiter concepts were examined in this study. The first is a Multi-Purpose Orbiter (MPO) which has all the functional capability described previously in Section 4.2, i.e., imaging for landing site survey and rover traverse planning, and telecommunications relay link between the rover and Earth. The second concept is a Dedicated Communications Orbiter (DCO) which, as its name implies, has much more limited capability. A brief description of each orbiter design concept follows.

Multi-Purpose Orbiter Configuration. The MPO (shown in Figure 14) is an eight-sided bus powered by two deployable solar panels, with a high-gain antenna on the Sun-facing side and a scan platform on the opposite side. The orbiter is assumed to be Sun-oriented to provide maximum solar cell efficiency. Communication to Earth uses the high-gain antenna which has a single degree of freedom, driven by an actuator. The antenna tracks Earth by rolling the spacecraft and tilting the antenna. Prior to deployment, the solar panels are stowed rolled up in containers, much like a window shade. Four attitude control assemblies are mounted on the ends of struts which extend radially between the solar panels. Also included is the relay antenna for rover telecommunications.

The major instrument carried by the orbiter is a 1-meter diameter by 2-meter long telescope for surface survey. In addition, the scan platform mounts an ASTROS-type tracker for wider angle views and a DRIRU to monitor the platform motion. The instrument's sheer volume dominates the configuration. The stringent pointing requirements on the platform dictate the use of a momentum wheel type of actuator drive on both axes of the platform. The momentum wheel actuators produce minimal disturbance on the rest of the orbiter and isolate the platform from the orbiter motions. The momentum wheel actuators, shown as .6 meter in diameter and .2 meter thick in Figure 14, are quite large and heavy. The use of the momentum wheel actuators dictates that the rotational axes pass through the center of mass for the respective axes. This then shapes the scan platform as two nested yokes, which in turn results in a large scan platform structure.

There are a number of technical challenges associated with the MPO concept, including data rate and volume, orbit determination, time required for mapping, imaging system pointing accuracy, and stereo reconstruction. A preliminary assessment based on the more detailed analysis presented in Reference 16 indicates that these challenges can all be met by currently available or near-term technology. The mass estimate for this MPO spacecraft is about 550 kilograms, excluding propellant and propulsion inerts.

Dedicated Communications Orbiter (DCO) Configuration. A specifically dedicated microwave relay communication system was also investigated. If the project were willing to provide a DCO in Mars-synchronous circular orbit (17,033 kilometers altitude), then the rover radio system can be considerably

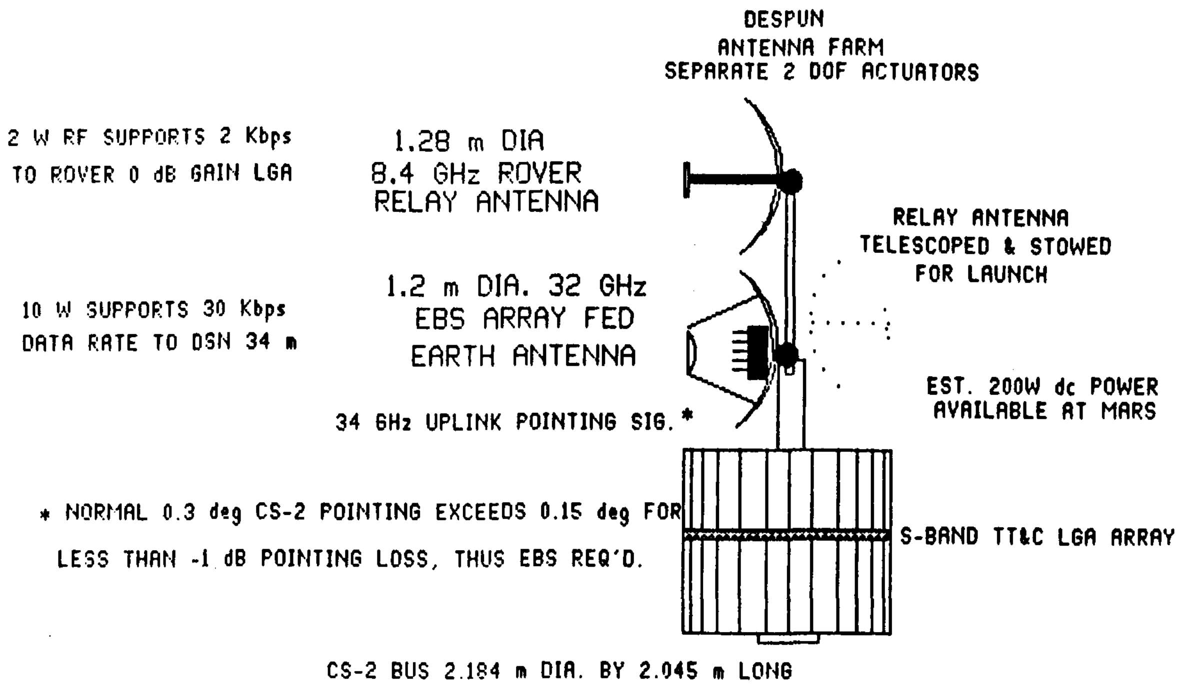

Figure 15. Dedicated Communications Orbiter Concept

simplified and nearly continuous communication could be obtained for rovers near the equator. Only low-gain antennas, which could permit communication while the rover is moving, would be required on the rover and the rover's pointing problems of high-gain antenna acquisition and tracking could be eliminated.

The relay spacecraft would require separately pointable high-gain antennas at the rover and Earth simultaneously. Figure 15 shows a concept for a modified spinner spacecraft (a version produced by Ford and the Japanese) with a despun antenna farm. A 10-watt array feed (for vernier beam pointing) transmitter at 32 GHz and a 1-meter diameter 60% aperture efficient parabolic antenna could provide the 30 kbps link relay to Earth. It would be desirable to have the 34 GHz Ka-band uplink signal available for uplink pointing reference and to free the X-band signals for unrestricted relay utilization.

The relay link design optimization for coding under bent pipe or remodulation conditions needs to be studied and analyzed. Also, the relay link optimum frequencies need to be studied regarding local environment noise,

noise added upon relay, antenna beam width pointing considerations, potential interference during simultaneous operations, data storage trade-offs, etc. Although the basic DCO spacecraft is less massive than the MPO design concept, the total system mass, including propulsion, is more than 600 kilograms if it is positioned in a Mars-synchronous orbit.

5.4 Mission Performance Summary

This section integrates the study results as related to the various flight mode options considered. The performance impact of these options on vehicle mass requirements and launch vehicle capability will be described and compared.

Trajectory Data. Mars launch opportunities repeat at intervals of about 25 months. The launch year affects the trajectory characteristics because of the varying geometry of the planetary orbits. Round-trip trajectories were generated for five consecutive launch opportunities between 1996 and 2005. The resulting data, listed in Table 9, assume conjunction-class flight profiles optimized on the basis of total velocity impulse; these point design examples will serve to illustrate the relationship between mission performance and launch opportunity. The mission parameters most affected by differences in launch year are the planet encounter velocities, the stay time at Mars, and the landing site latitudes accessible (without penalty) from elliptical orbits established about Mars. Note that near-equatorial sites are always accessible and that south polar regions are accessible from elliptical orbits for launches in 1996, 1998, or 2000/1. Landing in north polar regions is also possible but will require some orbit modification maneuvers, or, alternatively, entry out of polar circular orbits from which all latitudes can be reached.

Mars Orbit Insertion Options. An important measure of rover mission performance is the injected mass required at Earth launch. Injected mass is comprised of the total vehicle system sent to Mars; major elements include the system implementation of Mars orbit insertion (propulsive or aerocapture), the supporting orbiter, and the entry/lander system. The propulsive versus

Table 9

EARTH-MARS ROUND-TRIP CONJUNCTION-CLASS MISSIONS

	Launch Opportunity				
	1996	1998/9	2000/1	2003	2005
Dates					
Earth Launch	11-17-96	12-14-98	01-27-01	06-09-03	08-26-05
Mars Arrival	09-16-97	09-27-99	10-20-01	12-29-03	04-05-06
Mars Departure	08-14-98	01-28-01	04-17-03	07-13-05	07-17-07
Earth Return	08-06-99	09-05-01	11-10-03	01-20-06	04-24-08
Hyperbolic Velocity (km/s)					
Earth Launch	2.998	3.231	3.745	2.972	4.430
Mars Arrival	2.869	3.354	3.818	2.699	2.461
Mars Departure	2.685	2.537	2.725	3.845	3.202
Earth Return	3.914	3.781	2.991	3.264	2.910
Trip Times (days)					
Stay	332	489	543	561	468
Total	992	996	1,017	956	972
Accessible Periapsis Latitudes in a 500 km x 1 sol orbit	83° S , 27° N	88° S , 29° N	88° S , 37° N	47° S , 59° N	62° S , 38° N

aerocapture option is a significant performance trade-off issue for the rover mission; the other vehicle elements are not dependent on the Earth-Mars trajectory characteristics. Figure 16 compares the injected mass requirement associated with Mars aerocapture and all-propulsive capture for each of the five launch year opportunities. These results assume entry/landing from a 500 kilometer by 1-sol orbit, a 550-kilogram supporting orbiter, and a 640-kilogram rover. Mass scaling relationships for the aerocapture/aeromaneuver vehicle system and the propulsion system (with Earth-storable propellants) either were based on previous analyses or were established as part of this study. With aerocapture, the injected mass varies between 2,700 and 3,050 kilograms, allowing the rover mission to be accomplished by the Shuttle/IUS(II) launch vehicle, with the possible addition of an Injection Module kick stage. Propulsive capture requires a 25 to 50 percent increase in injected mass, is much more sensitive to launch opportunity, and needs a greater launch capability as represented by the expendable Titan IV/Centaur G', which can accomplish the mission in any launch year with a large mass margin.

A performance comparison of elliptical versus circular orbit capture at Mars is shown in Figure 17 for the 1996 launch opportunity. By its nature, aerocapture is virtually insensitive to orbit size. With propulsive capture, however, insertion to a low-altitude circular orbit requires a much larger velocity impulse and a corresponding 45 percent increase in injected mass, from 3,690 to 5,350 kilograms. The injected mass margin of the Titan IV/Centaur G' is reduced to only a few hundred kilograms and would disappear for launches in either 1998 or 2000.

Considerable mass savings would be possible if the support orbiter were not a required mission element. For launch in 1996, the sensitivity ratio of injected mass to orbiter mass (in units of kilograms/kilogram) is 1.4 for aerocapture, 1.8 for propulsive capture to elliptical orbit, and 2.6 for propulsive capture to circular orbit. The reduction in injected mass, even for propulsive capture to circular orbit, would allow greater flexibility in the use of the Shuttle/IUS launch vehicle. Nevertheless, this apparent advantage is probably insufficient to obviate the need for a support orbiter, which has been shown to be vitally important to the rover mission's function.

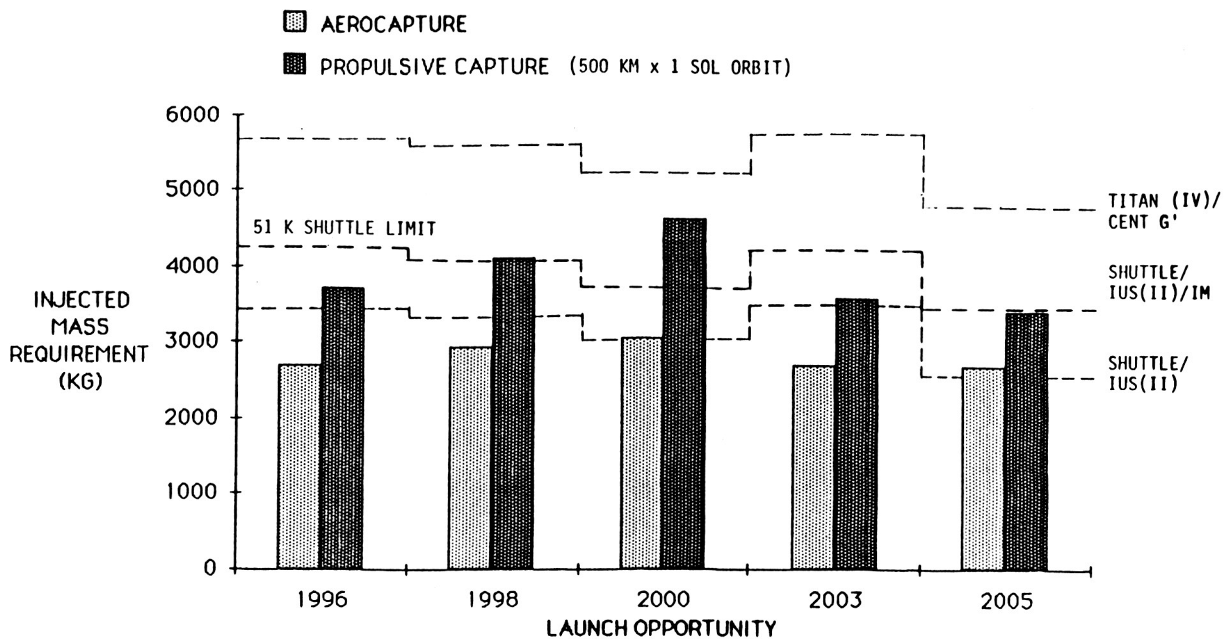

Figure 16. Mars Rover Mission Mass Performance

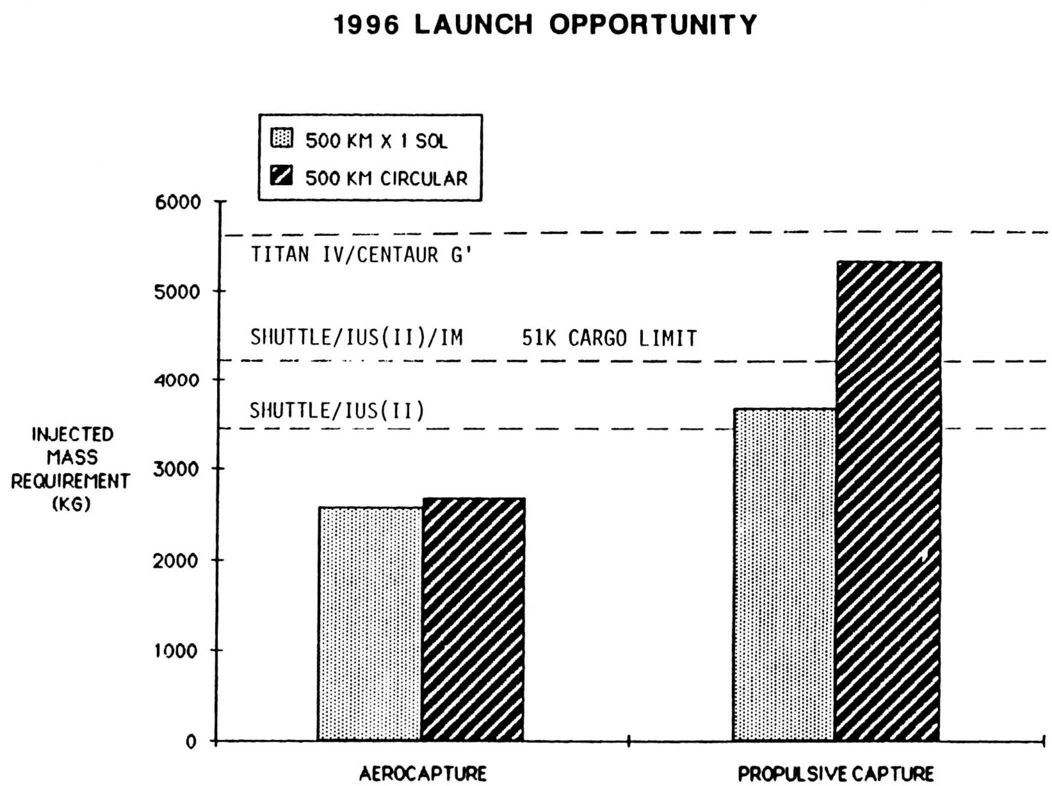

Figure 17. Mars Rover Mission Mass Performance Comparison of Elliptical and Circular Orbit Insertion

Reference Mass Statement. A preliminary but comprehensive requirements analysis of the various subsystems comprising the rover mission was undertaken as part of this study. Plausible design points for each of the Mars aerocapture and all-propulsive capture options are summarized in Table 10 (further details may be found in Ref. 16). In each case the reference design assumes a full-capability support orbiter, a high L/D aeromaneuvering entry vehicle, a lander module with a certain degree of hazard avoidance/tolerance, and a semi-autonomously operated wheeled rover with significant sampling and on-surface science capability. The main difference between these options is the means of Mars orbit insertion. All-propulsive capture requires a total propellant loading of 1,373 kilograms compared to only 477 kilograms for aerocapture - almost a factor of 3 increase. Interestingly however, the combined dry mass of the aerocapture shell and its propulsion system inerts is 295 kilograms, slightly more than the 235 kilograms of inerts for the all-propulsive option. even though the total injected mass of the all-propulsive option is 32 percent higher, it is reasonable to expect that the aerocapture option would actually cost somewhat more to develop because of its advanced technology and larger dry mass requirements. This was verified by a very preliminary cost estimate for the rover mission project (two sites, through launch + 30 days) which was determined to be 2.0 - 2.2 billion in FY 1987 dollars, including a medium level of heritage from other flight projects and a liberal 30 percent contingency.

Table 10

MARS ROVER MISSION MASS SUMMARY FOR A PLAUSIBLE REFERENCE DESIGN

	Total Mass in Kilograms			
	Mars Aerocapture[1]		Propulsive Capture[1]	
Rover [2]	607		607	
Lander Module	336	(82)*	336	(82)
Parachute Systems	87		87	
Aeromaneuvering System	469	(106)	469	(106)
Aerocapture Shell	208		---	
Orbiter [3]	894	(289)	1,939	(1,185)
Bioshield	29		29	
LV Adapter	79		104	
Injected Mass	2,709	(477)	3,571	(1,373)
Shuttle/IUS(II) Margin ...... 1996 Launch	740		680	(w/Injection Module)

* Propellant mass in ( )

[1] 500 km x 1 sol orbit

[2] with 90 kg science payload

[3] with 61 kg science payload

ACRONYMS AND ABBREVIATIONS

ARC	NASA/Ames Research Center
CARD	Computer-Aided Remote Driving
COMPLEX	Committee on Planetary and Lunar Exploration
DCO	Dedicated Communications Orbiter
DRIRU	Dry-Tuned Rotor Inertial Reference Unit
IUS	Inertial Upper Stage
JPL	Jet Propulsion Laboratory
JSC	NASA/Lyndon B. Johnson Space Center
L/D	Lift-to-Drag Ratio
MESAG	Mars Exploration Strategy Advisory Group
MPO	Multi-Purpose Orbiter
MRSR	Mars Rover/Sample Return
OMV	Orbital Maneuvering Vehicle
OTV	Orbital Transfer Vehicle
RHU	Radioisotope Heating Unit
RTG	Radioisotope Thermoelectric Generator
SAIC	Science Applications International Corporation
SSB	Space Science Board
SSEC	Solar System Exploration Committee
USGS	U.S. Geological Survey

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